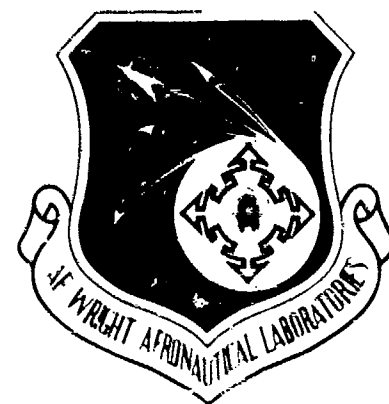


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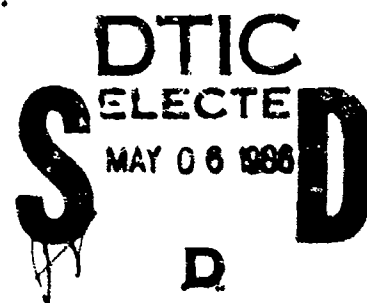
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Volume III On-Board Inert Gas Generator System (OBIGGS) Studies
Part 2 Fuel Scrubbing and Oxygen Evolution Tests

VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND
EXPLOSION HAZARDS

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January 1986

Final Report for Period February 1981-October 1984

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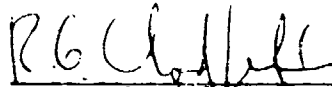
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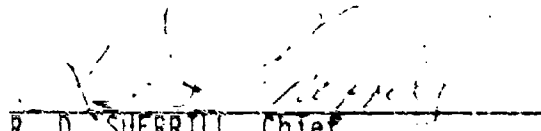
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This technical report has been reviewed and is approved for publication.



R. G. Clodfelter, Chief
Fire Protection Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

FOR THE COMMANDER



R. D. SHERRILL, Chief
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Aero Propulsion Laboratory

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II. TITLE

VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE
AND EXPLOSION HAZARDS

Volume III On-Board Inert Gas Generator System (OBIGGS) Studies

Part 2 Fuel Scrubbing and Oxygen Evolution Tests

This report is one of the set of aircraft fire protection reports contained in
AFWAL-TR-85-2060 as listed below:

Volume I Executive Summary

Volume II Aircraft Engine Nacelle Fire Test Program

Part 1 Fire Detection, Fire Extinguishment and Hot Surface
Ignition Studies

Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

Volume III On-Board Inert Gas Generator (OBIGGS) Studies

Part 1 OBIGGS Ground Performance Tests

Part 2 Fuel Scrubbing and Oxygen Evolution Tests

Part 3 Aircraft OBIGGS Designs

PREFACE

Aircraft fire protection research conducted by the Boeing Military Airplane Company under Contract F33615-79-C-2063 is discussed in this report. Most of the research was carried out in newly activated facilities, the Aircraft Engine Nacelle (AEN) simulator, and the Simulated Aircraft Fuel Tank Environment (SAFTE) simulator located at Wright-Patterson Air Force Base and was conducted between February 1981 and October 1984. The contract was sponsored by the Air Force Wright Aeronautical Laboratories (AFWAL) and the Joint Technical Coordinating Committee for Aircraft Survivability (JTCC/AS). Guidance was provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSH), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 07, and Work Unit 86. Gregory W. Gandee, Terrell D. Allen, and John C. Sparks were the Government project engineers.

The results are presented in three volumes with Volumes II and III subdivided into parts. Volume I summarizes the research conducted under this program, describes the test facilities used, and highlights important findings. Volume II discusses research related to engine compartment (nacelle) fire protection. Testing was done primarily in the AEN simulator but some small scale testing was also performed in Boeing facilities in Seattle. Volume III discusses fuel tank fire protection research studies performed under this contract. Most of this work was focused on on-board inert gas generator system (OBIGGS) technology. Much of the testing related to OBIGGS development was conducted in the SAFTE simulator but again some related small scale testing was done in Seattle. The contents of the three volumes are listed below:

Volume I Executive Summary

Volume II Aircraft Engine Nacelle Fire Test Program

Part 1 Fire Protection, Fire Extinguishant and Hot Surface Ignition
 Studies

Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

Volume III On-Board Inert Gas Generator System (OBIGGS) Studies

Part 1 OBIGGS Ground Performance Tests

Part 2 Fuel Scrubbing and Oxygen evolution Tests

Part 3 Aircraft OBIGGS Designs

Boeing wishes to acknowledge the contributions of the design and technical personnel of Technical/Scientific Services, Inc. (TSSI) for their support to this program and to R. G. Clodfelter of the Air Force for his technical guidance during the research studies and for his efforts to develop these national facilities for generalized investigations of techniques to improve aircraft fire safety.

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1.0 INTRODUCTION

Aircraft fuel tank inerting depends on limiting the oxygen concentration in the vapor space (ullage) to levels that will not support combustion. The consensus of many previous studies (see Ref. 1) is that sustained combustion cannot occur within the fuel tanks if the oxygen concentration is 9% or less (by volume). One basic problem in maintaining a safe ullage is managing the release of oxygen dissolved in the fuel. Significant amounts of oxygen would be carried into the fuel tank when the tank is filled (to the expansion space volume) with air saturated fuel. Natural evolution of dissolved oxygen during airplane climbout could quickly cause an initially inert ullage to become unsafe. The common method for removing the dissolved oxygen is to scrub the fuel with an inert gas. Scrubbing involves exposing the fuel to a multitude of small inert gas bubbles in a mixing process. The concentration gradients between the gases in the bubbles and the dissolved oxygen in the fuel tend to cause the composition of the gases in the bubbles to come to equilibrium with dissolved gases in the fuel. The mechanism allows the bubbles to remove oxygen from the fuel, deposit oxygen and scrub gases in the ullage, and subsequently expel these gases from the airplane through the fuel tank vent system climb valves.

Fuel oxygen solubility and fuel scrubbing processes are amenable to modeling. Experimental data are required for model validation. Previous studies, such as those described in Ref. 2, present valuable data but lack the systematic approach required for validating an analytic model. Therefore, under this contract, experiments were performed which were directly applicable to the validation process. Oxygen solubility and fuel scrubbing phenomena were studied in the Boeing Fuels Laboratory in Seattle, Washington, in 1982. Fuel scrubbing was studied using a C-5A scrub nozzle with both gaseous nitrogen and nitrogen enriched air (NEA).

These tests and the analytic model validation results are described in Section 2.0 of this document. The 1982 tests did not include investigation of other important variables in the dissolved gas evolution process, such as:

- o the effect of decreasing ullage pressure (simulated climbout);
- o the effect of decreasing fuel quantity (fuel burn);

- o the effects of slosh and vibration and fuel recirculation; and
- o fuel scrubbing during a simulated mission.

These variables were examined in tests performed in April, 1983, using the Simulated Aircraft Fuel Tank Environment (SAFTE) test facility at Wright-Patterson AFB, Ohio. The tests were based on a mission profile and fuel depletion schedule for a KC-135 airplane. The SAFTE test facility, test procedures and results from the simulated missions investigations are described in section 3.0. Conclusions and recommendations are combined in Section 4.0.

2.0 FUEL OXYGEN SOLUBILITY AND SCRUB NOZZLE PERFORMANCE

Testing to gain further insight into fuel scrubbing characteristics was a two step process. The first step was to check, using data from a solubility evolution test, whether a model based on classical relationships and published solubility coefficients could adequately predict the final or equilibrium ullage oxygen concentration in a test set up where an initially inert ullage and air saturated fuel were vigorously mixed to produce equilibrium conditions. This process would be analogous to a closed cycle scrub system in which ullage gases were constantly circulated through the fuel until equilibrium was attained. The second step was to conduct scrubbing tests for the more realistic case in which the scrub gas enters the tank from an external source and excess ullage gases are vented to the atmosphere. The latter tests were conducted using a production type C-5A scrub nozzle using both gaseous nitrogen (GN_2) and nitrogen enriched air (NEA).

Specific objectives of the scrubbing tests were:

- o to verify the Boeing computer model (Appendix A) for gas/fuel mixing and solubility of gases in the fuel;
- o to map the performance of the C-5A scrub nozzle; and
- o to validate and enhance the Boeing developed code for predicting ullage gas compositions with fuel scrubbing.

2.1 Oxygen Solubility in JP-4 and JET A Fuels

This section describes the bench scale solubility evaluation (also referred to as shake tests) used to verify the basic equations described in Appendix A. For these tests both GN_2 and NEA₉ were used with JET A and JP-4 fuels. Since the test results would be sensitive to both gas solubility values and to the nature and extent of the mixing process, these features of the model could be examined by comparing test and prediction results.

2.1.1 Test Hardware

The solubility test set-up is shown schematically in Figure 1. A Beckman Model 0260 oxygen analyzer and a Model 39556 oxygen sensor were used to measure the ullage and fuel concentrations. This probe was a polarographic membrane-type sensor whose output current was proportional to the partial pressure of oxygen in the sample. The time response of the analyzer was of the order of 1 second and the estimated measurement uncertainty was $\pm 5\%$ of reading.

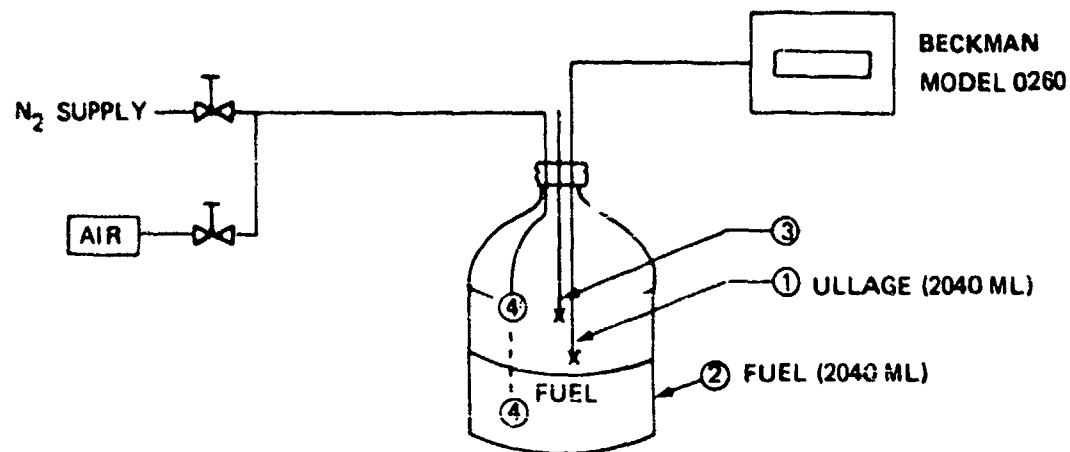
2.1.2 Test Procedures

Manual temperature compensation of the O_2 analyzer was periodically performed during each of the test runs and the sensor was calibrated prior to each test using the following procedure:

- o Air was bubbled through the fuel until a constant reading of the O_2 sensor was obtained. Readings in both ullage and in fuel were recorded.
- o Nitrogen gas was bubbled through the fuel until a constant reading of the O_2 sensor was obtained. Both ullage and fuel measurements were recorded.
- o Temperatures in each step above were recorded.
- o Calibration curves for fuel and ullage, i.e., actual O_2 (% volume) versus instrument reading were constructed.

Following the probe calibration, air was bubbled through the fuel until saturated at ambient pressure and temperature. The saturation condition was verified by monitoring the dissolved oxygen probe outputs. The following steps were then performed to complete the test:

- o The ullage volume was purged with inert gas (approximately 1 to 2 minutes). The purge process was monitored with the oxygen sensor.



- 1 BECKMAN POLAROGRAPHIC OXYGEN SENSOR, MODEL 39556
- 2 1-GALLON PLASTIC JUG (TOTAL VOL = 4080 ML)
- 3 THERMOCOUPLE
- 4 ULLAGE PURGE LINE

Figure 1 Test Set-Up for the Gas/Fuel Solubility Evaluation

- o The probe was quickly removed, the test container capped, and then the test container was shaken for approximately 1 minute.
- o After shaking, approximately 10 seconds were allowed for stabilization.
- o The cap was removed, the probe inserted in the ullage, and the gap in the neck of the container was plugged to prevent back diffusion of air; the reading was recorded.
- o The probe was inserted into fuel and the reading recorded.

2.1.3 Test Results

Test results for the solubility evaluation are summarized in Figures 2 and 3 for JET A and JP-4, respectively. These figures show final ullage and final fuel concentrations as a function of ullage concentration prior to mixing; predicted results are also plotted for comparison. As noted the fuel was approximately air saturated prior to each mixing procedure.

The following observations can be made from these figures:

- o For JET A (Figure 2), the measured and predicted values of oxygen concentrations for both ullage and fuel were within 1%; the measured values were higher than predicted in the ullage and lower than predicted in the fuel. This discrepancy could be due to an actual solubility coefficient that was higher than that used for the predicted values.
- o For JP-4 (Figure 3), variations up to 2% between measured and predicted values of oxygen concentration were observed.

Note that the slope of the lines connecting the initial and final concentration points are nearly the same for both experiment and analysis. This commonality of slopes suggests that the equations describe the mixing process reasonably well, i.e., in going from an unmixed non-equilibrium state to a fully mixed equilibrium condition. This ability is important since the computer model is based on a series of quasi-steady state mixing steps as scrub gas is introduced into the fuel mass (see Appendix A).

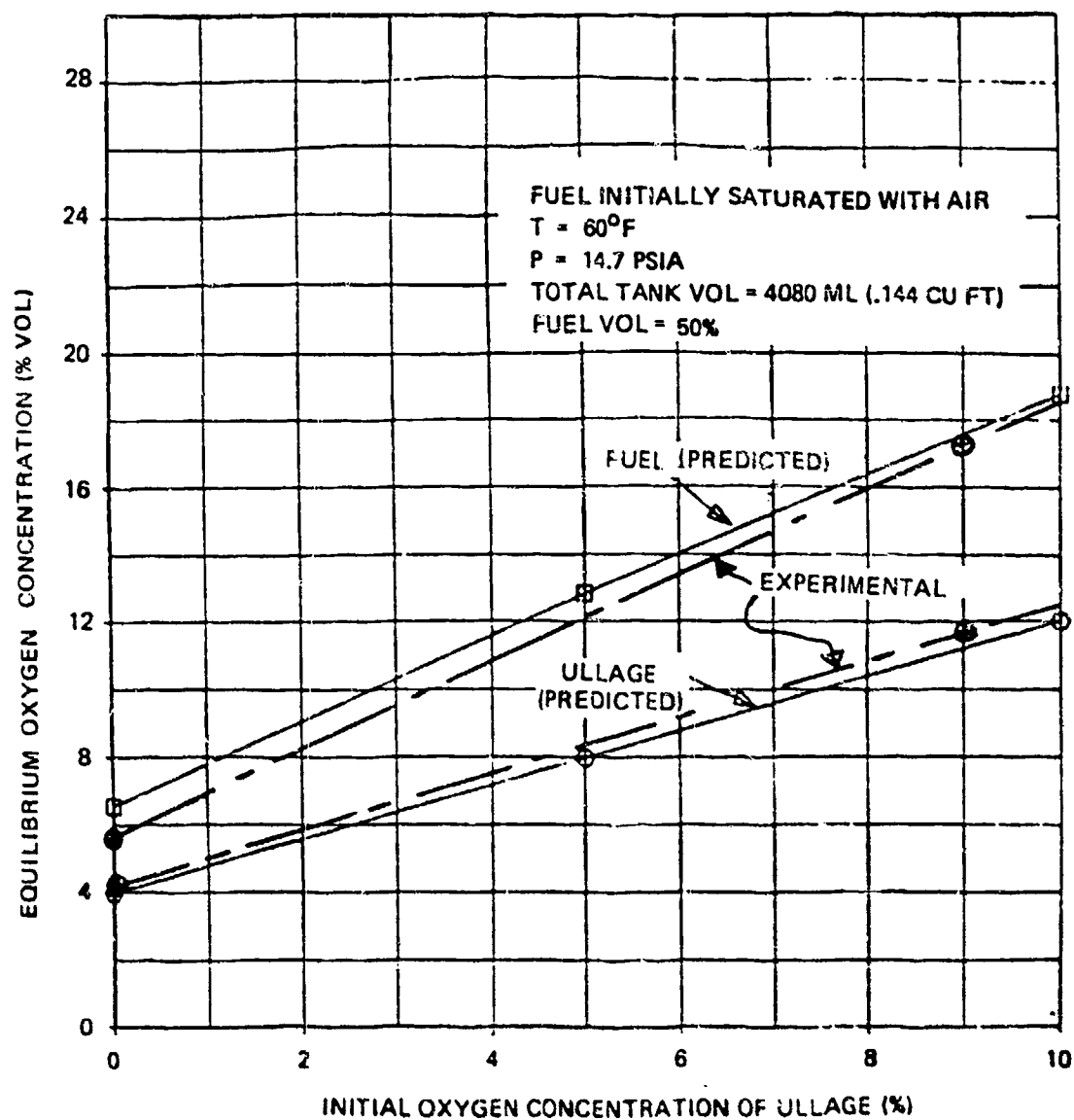


Figure 2 Results of the Solubility Evaluation Using Jet A Fuel

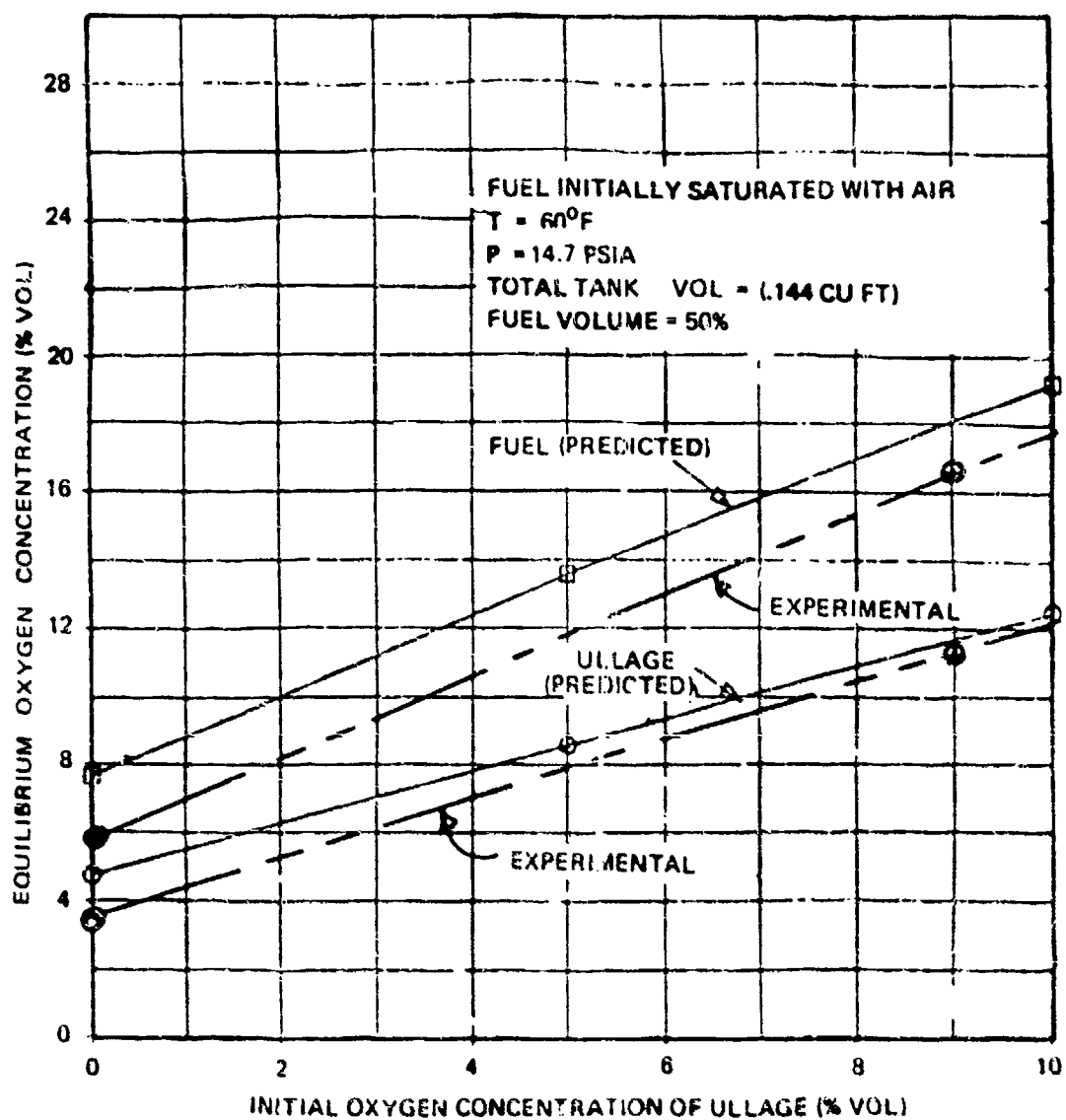


Figure 3 Results of the Solubility Evaluation Using JP-4 Fuel

While the agreement between measured and predicted values was good, potential sources of error included:

- o The computer model used average values for JP-4 and JET A solubility (Ref. 3). A range of solubility coefficients is possible for samples within one fuel type.
- o The effect of the duration of shaking on the equilibration process was not examined parametrically.
- o The oxygen probe was subject to a slight calibration drift as the test proceeded.
- o Fuel vapor pressure effects were not included in the computer model.

2.2 Fuel Scrubbing Tests

This section describes tests to evaluate scrubbing effects in the Boeing 156-gallon fuel tank using the C-5A scrub nozzle.

2.2.1 Test Hardware

The scrub nozzle test apparatus (Figure 4) consisted of a 20.3 ft³ rectangular tank filled with fuel to a height of 36 inches and vented to the atmosphere. In all tests, the ullage volume (2.08 ft³) was 10% of the total volume. The scrub nozzle was a single nozzle mounted 3 inches from the tank bottom as indicated and angled toward one wall to produce maximum circulation and stirring of the fuel. Only JET A fuel was used in the scrub nozzle tests.

The C-5A scrub nozzle was an ejector type with primary and secondary nozzles and a mixing tube. The primary nozzle contained a swirl vane to help mix the motive liquid fuel flow with the entrained gas. The 1.2 gpm flow rate used in these tests is representative of a C-5A single nozzle tank bay (316 gal). The inert gas and fuel phases were mixed and discharged from the mixing tube which had an exit internal diameter of 0.22 inches. According to Lothrigel (Ref. 2), bubbles discharged from the mixing tube should be about 1/10 of the exit diameter of the mixing tube.

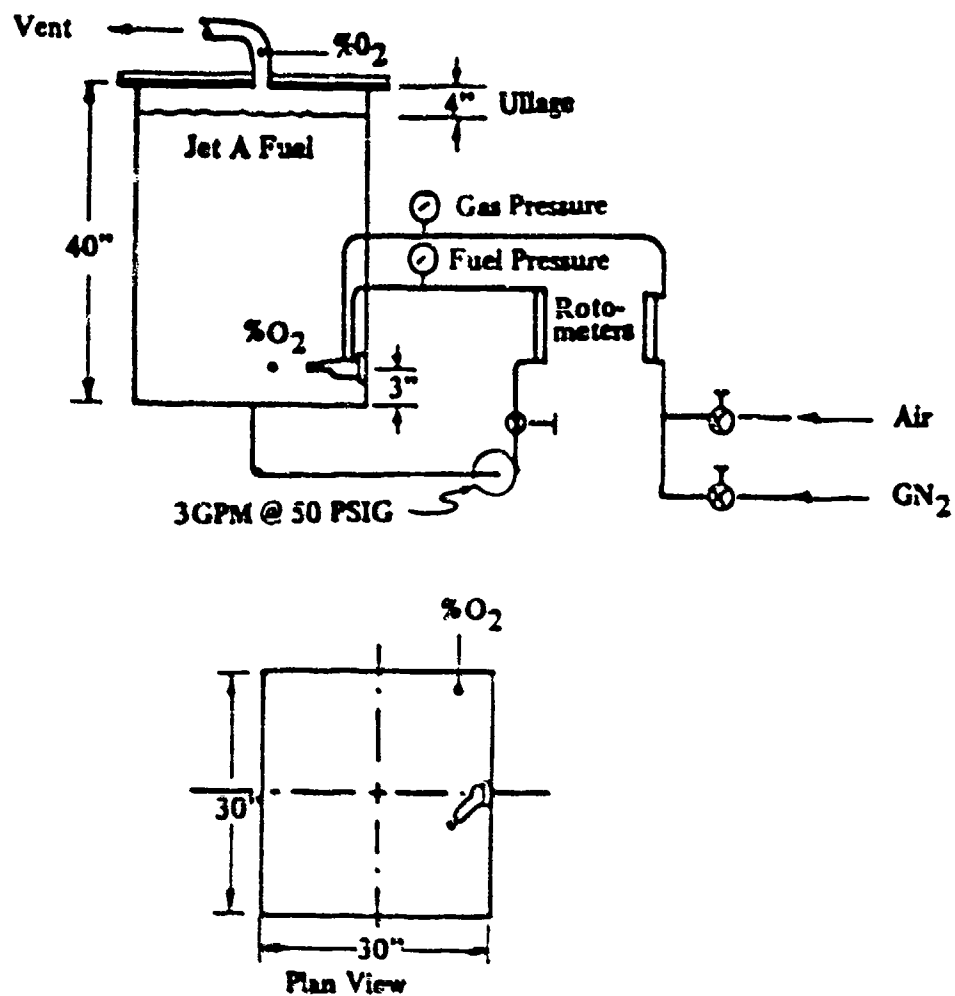


Figure 4 Test Set-up for the Scrub Nozzle Evaluation

The test tank was fitted with a plexiglas lid for viewing the circulation patterns and bubble distributions. A hole in the center of the lid provided access for the Beckman polarographic membrane probe into the tank interior. Thermocouples were used to measure fuel and ullage temperatures, and calibrated rotometers were used to measure motive fuel and inert gas flow rates. The motive fuel and entrained gas supply pressures were measured with Bourdon tube type gauges.

2.2.2 Test Procedures

Measurements were first taken to establish pressure-flow performance characteristics of the scrub nozzle. This process was done by measuring pressure and flow rates for the fuel and scrub gas streams while varying supply pressures. Flow rates in the range required to scrub the Boeing 156 gallon and the USAF SAFTE tanks (573 gallons) were of special interest.

These flow rates had been estimated beforehand using published C-5A inerting data (Ref. 4). No oxygen concentration measurements were taken during the performance tests.

After this initial testing, a scrubbing evaluation was performed with 140 gallons of JET-A fuel using gas flow rates of 0.037, 0.074, 0.0925, and 0.11 pounds per minute, and a fuel flow rate of 1.2 gallons per minute through the scrub nozzle. Most of the tests were conducted with GN_2 with a limited number of runs using NEA_9 (nitrogen enriched air with a 9% oxygen content by volume).

The following procedure was used for this test:

1. The 156-gallon tank was filled with approximately 140 gallons of JET A fuel.
2. Air was bubbled through the fuel sample using the scrub nozzle for several minutes. The oxygen probe was mounted in the fuel.
3. The fuel/gas scrubbing stream was then introduced at the desired ratio, and the oxygen concentration in the fuel was measured as a function of time.

4. Upon reaching the equilibrium concentration, which required about 30-40 minutes, the scrubbing was stopped.
5. Air was bubbled through the fuel for several minutes to re-saturate the fuel with air.
6. The oxygen probe was relocated to the ullage. The fuel/gas scrubbing stream was reintroduced at the above ratio and the oxygen concentration in the ullage was measured as a function of time.
7. Steps 2 through 6 were repeated for the next fuel/gas flow ratio of interest.

2.2.3 Test Results

This section describes the results of the scrubbing evaluation using JET A, GN_2 and NEA_9 .

2.2.3.1 Results of Nozzle Performance Tests

Results of the scrub nozzle pressure-flow performance characteristic tests are summarized in Figure 5. The upper part of the figure shows the nozzle performance characteristics for fuel flow. Based on calculations from data from the C-5A nozzle and Ref. 2, the fuel flow rate required for the 156 gallon tank was estimated to be 1.2 gallons per minute. As indicated in the figure, this flow rate required a supply pressure of approximately 16 psig.

Gas flow rates for the C-5A were also calculated (based on a 1.2 gallons per minute flow rate) along with the required gas pressure (lower part of Figure 5). It was found that a delivery pressure of 1 psig was sufficient to deliver the 0.05 pounds per minute gas flow required for the optimum gas/fuel mixing process.

Based on these results, an estimate was made for the fuel and gas delivery flow rates required for the 573-gallon SAFTE tank at Wright-Patterson AFB. As indicated in the figure, these values were given as 2.36 gpm fuel at 57 psig and 0.0925 pounds per minute inerting gas. The required gas delivery pressure

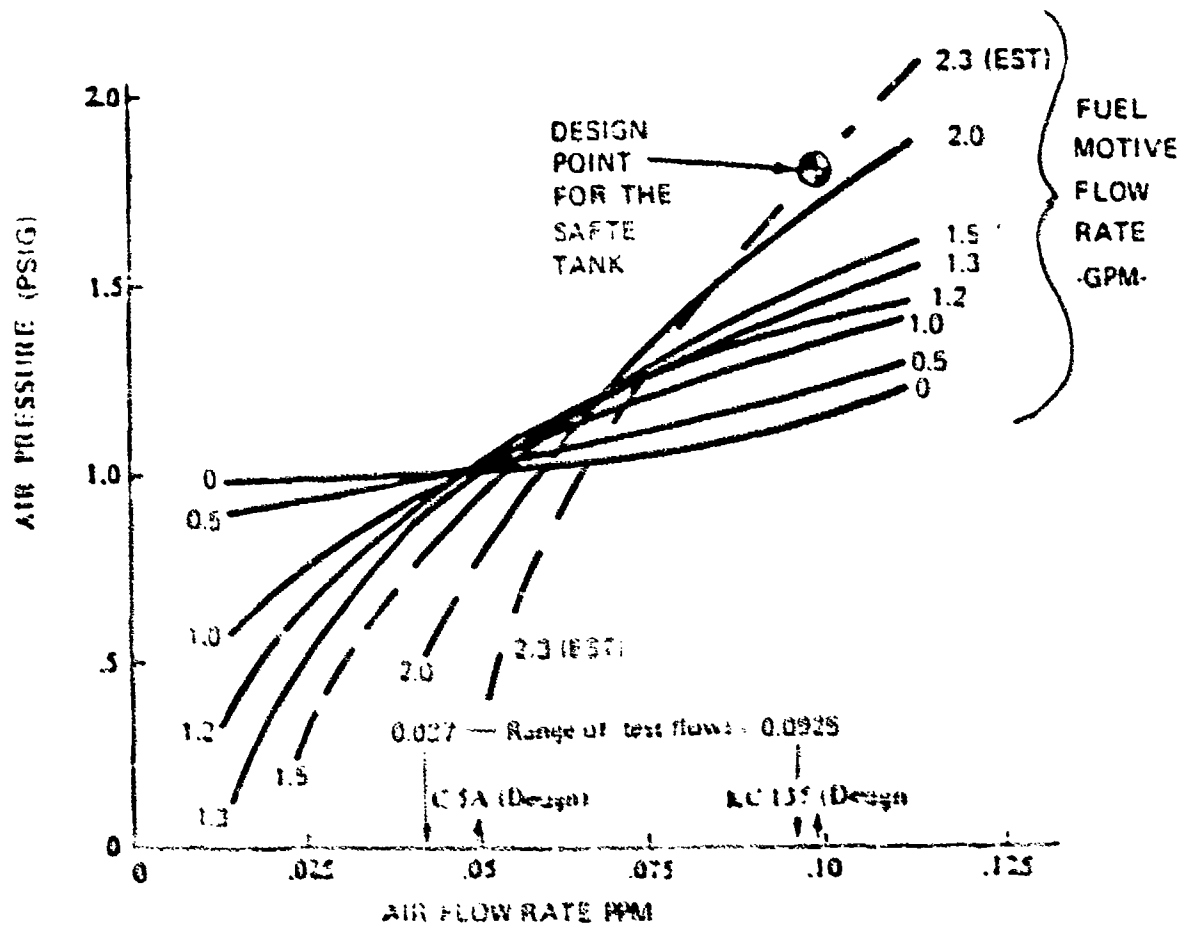
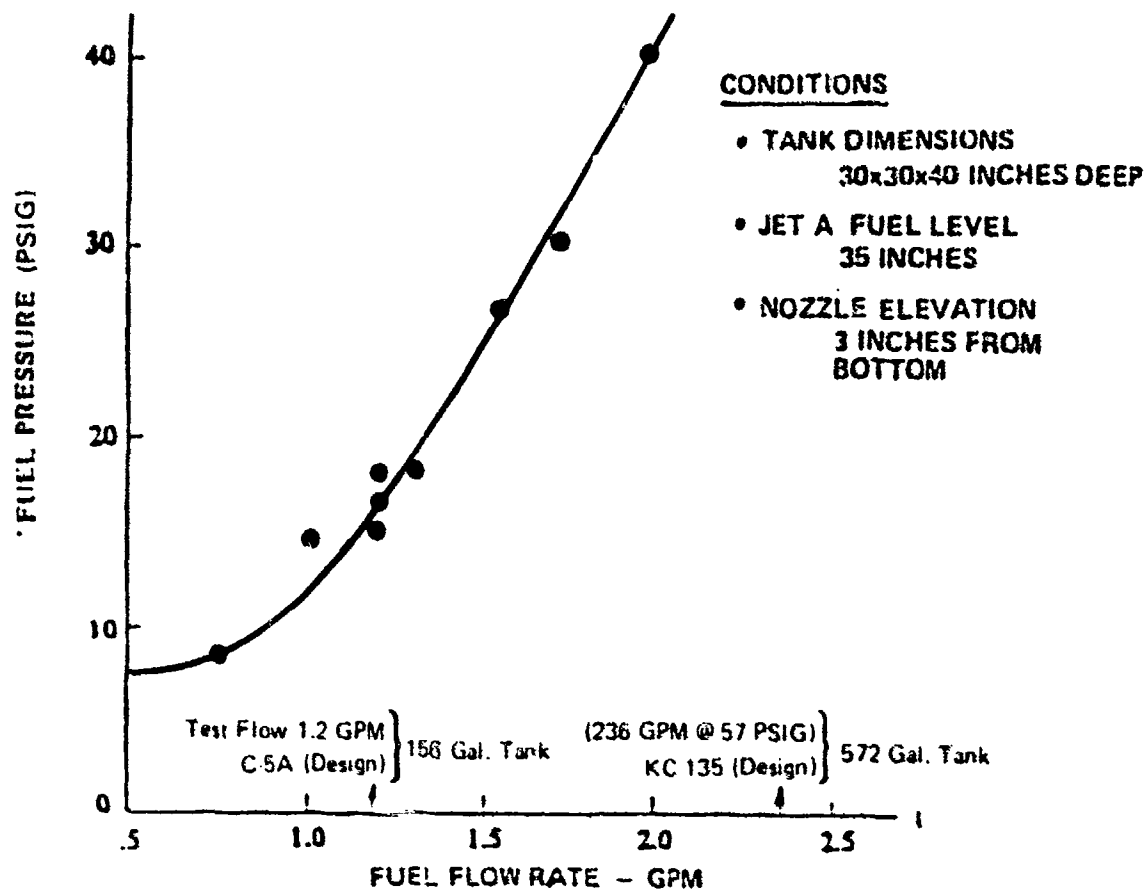


Figure 5 C-5A Scrub Ejector Nozzle Pressure-Flow Characteristics

was in the range 2-3 psig. The method used to estimate these flow rates is described in Appendix B.

2.2.3.2 Results of Scrubbing Tests Using the 156-Gallon Tank

Results from the scrubbing tests using pure GN_2 are summarized in Figures 6 through 9. Comparisons between measured and predicted ullage oxygen concentrations are given for 0.037 pounds per minute (Figure 6), 0.074 pounds per minute (Figure 7), and 0.0925 pounds per minute, the estimated SAFTE flow rate (Figure 8). The agreement between measured and predicted values was reasonable with the measured values being generally higher. Figure 9 shows a comparison between measured and predicted oxygen concentrations in the fuel for GN_2 scrub flow at 0.0925 pounds per minute; again the agreement is good. The observed differences are probably due to the factors mentioned earlier for the solubility tests including probe calibration drift, incomplete initial fuel saturation, and, in the case of the model, uncertainties in the value of the solubility coefficients and no accounting for incomplete scrub mixing.

Ideally, a 100% efficient scrub nozzle would produce complete scrub mixing or equilibration. The actual efficiency of the nozzle can be estimated using measured and predicted fuel dissolved oxygen concentrations. This calculation is presented in Appendix C.

To assess the effects of NEA on scrubbing efficiency, an NEA_9 mixture was blended and delivered to the scrub system at 0.0925 pounds per minute. A comparison between measured ullage concentrations using GN_2 and NEA_9 for this flow rate is shown in Figure 10. This plot suggests that NEA does not affect nozzle efficiency as both curves approach their respective final minimum O_2 concentration within approximately 20 minutes. The figure also indicates that the agreement between the measured and predicted values for the NEA_9 case is comparable to that achieved with GN_2 .

One additional scrub test was performed using an initially inert ullage ($\approx 100\% \text{GN}_2$) and GN_2 inertant flow at 0.0925 pounds per minute. The results (Figure 11) reveal a peak in ullage O_2 concentration of about 3% approximately 3 minutes from the start of scrubbing, whereas the fuel concentration falls continuously. A higher rate of scrubbing would decrease the peak values and cause the peak value to occur earlier.

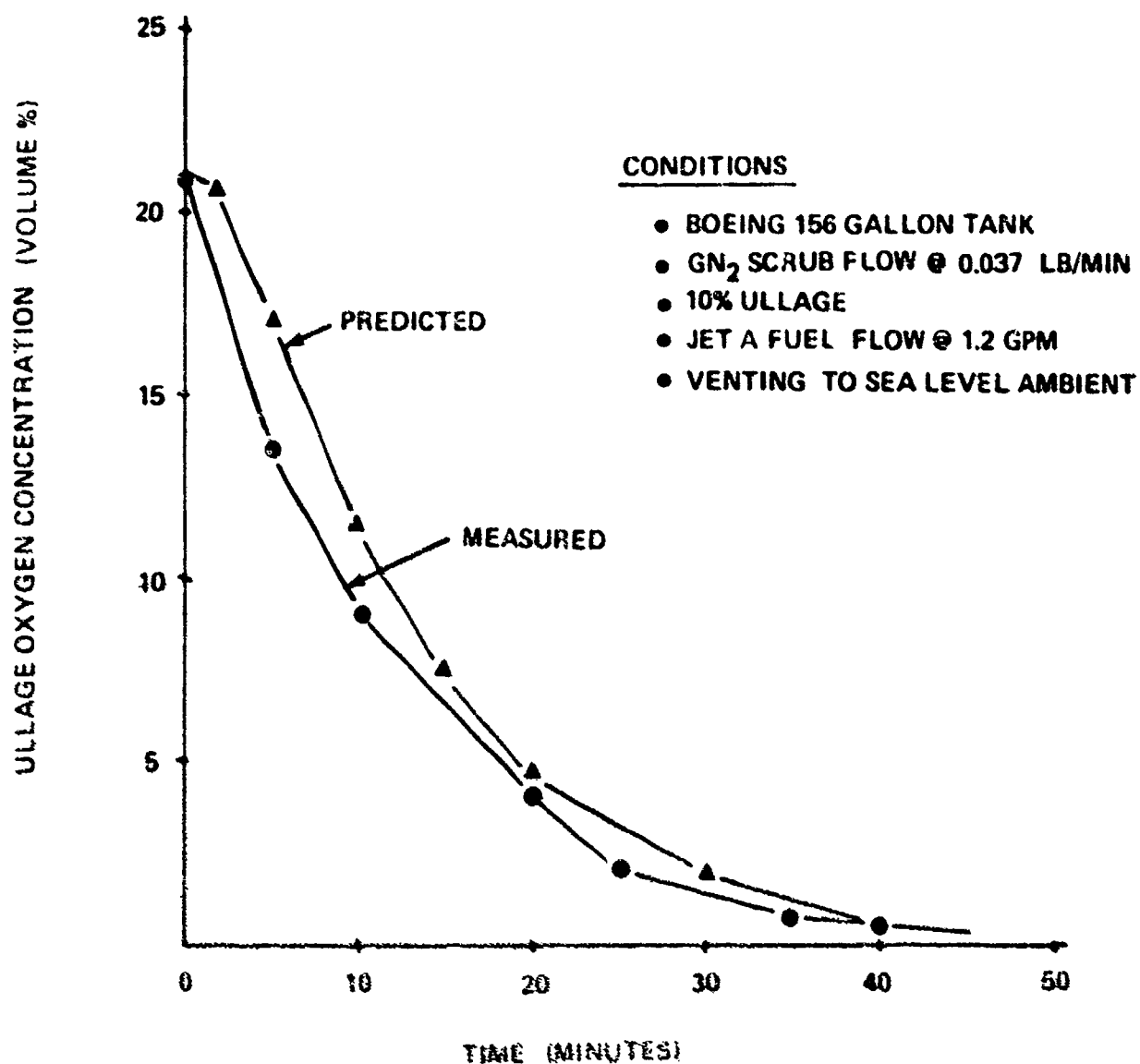


Figure 6 Measured and Predicted Ullage Oxygen Concentrations
with GN_2 Scrubbing at 0.037 LB/MIN

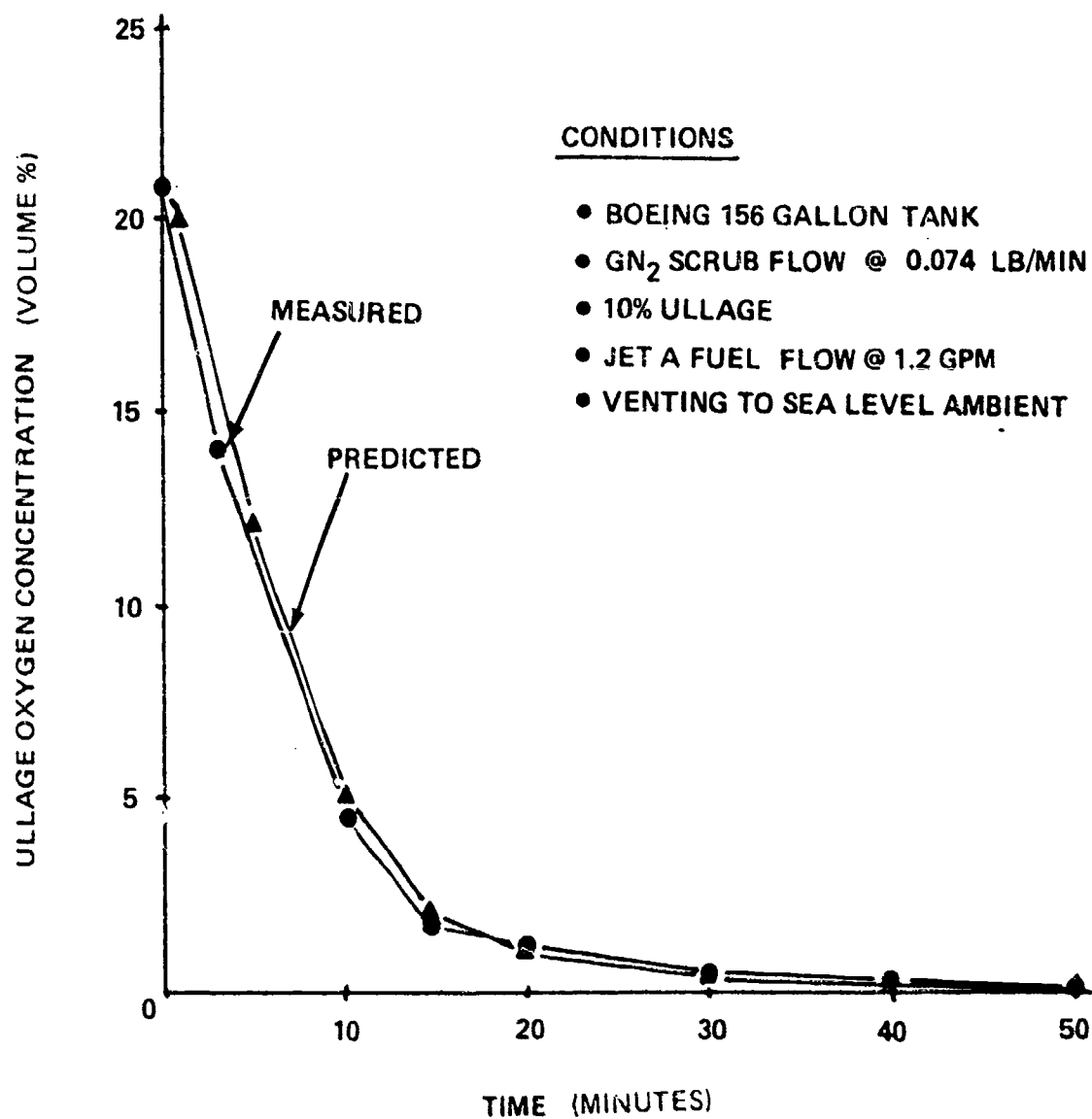


Figure 7. Measured and Predicted Ullage Oxygen Concentrations with GN_2 Scrubbing at 0.074 LB/MIN

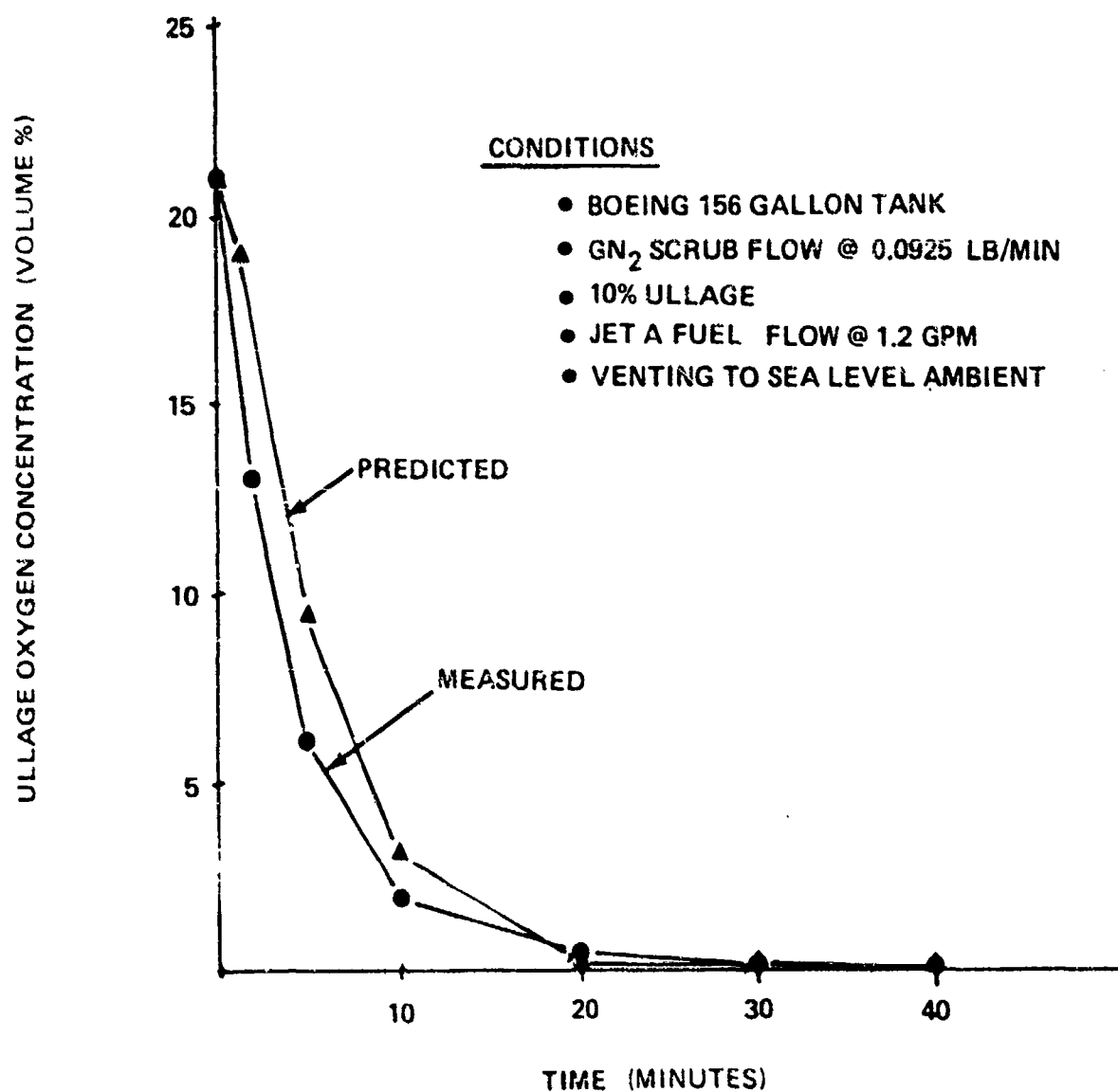


Figure 8. Measured and Predicted Ullage Oxygen Concentrations
with GN_2 Scrubbing at 0.0925 LB/MIN

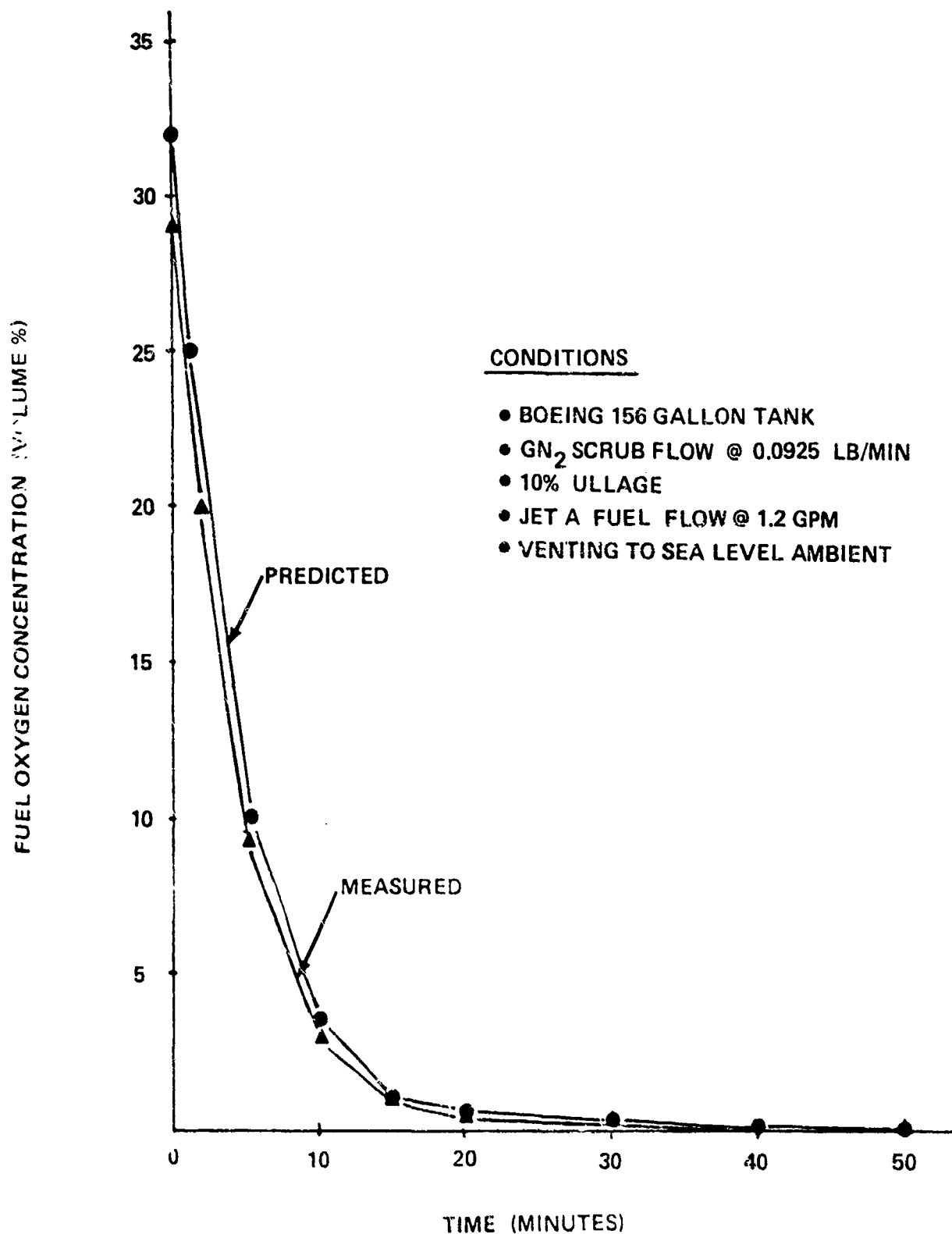


Figure 9 Measured and Predicted Fuel Oxygen Concentration
with GN_2 Scrubbing at 0.0925 LB/MIN

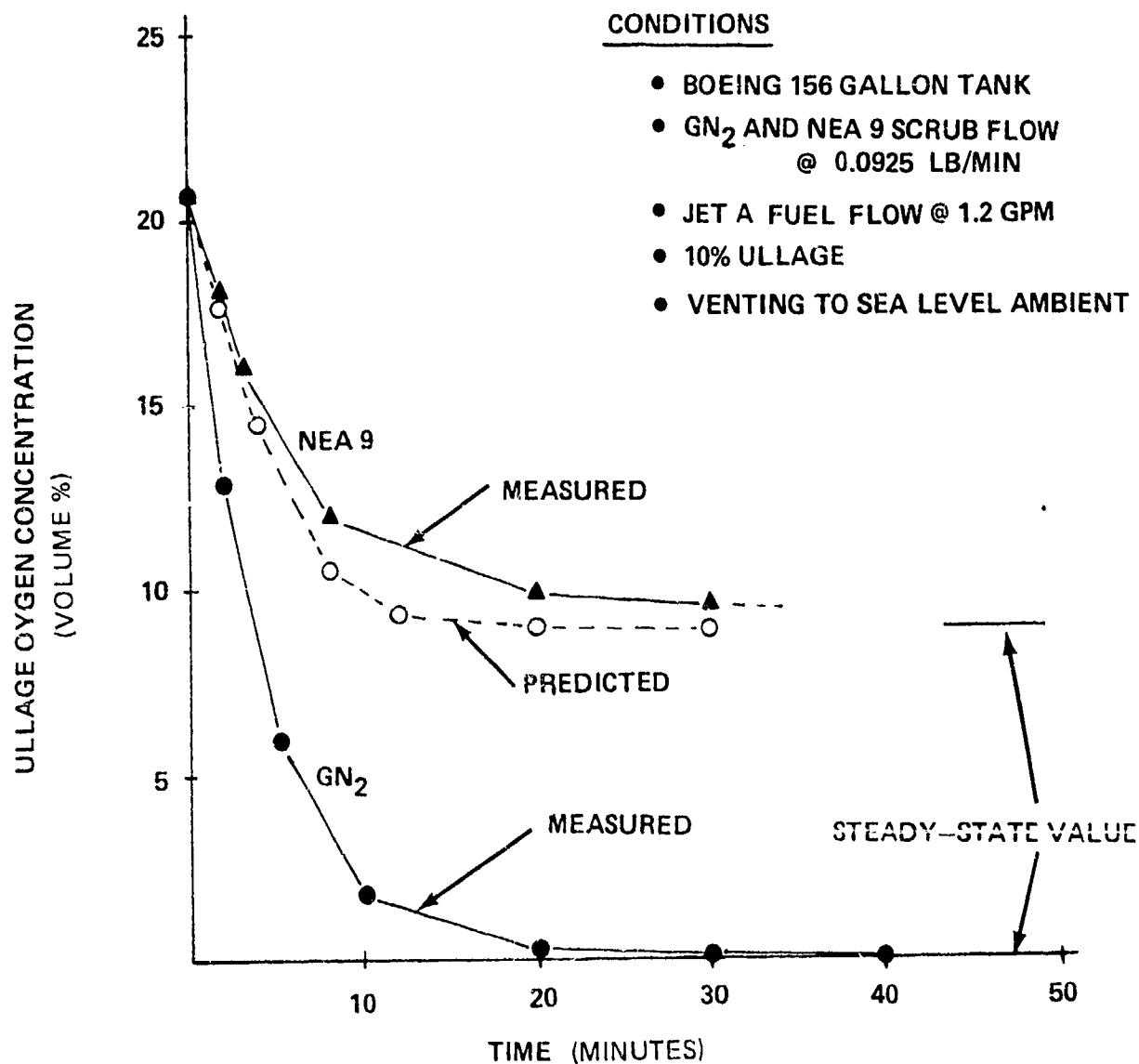


Figure 10 Measured and Predicted Ullage Concentrations
Using GN_2 and NEA_9 at 0.0925 LB/MIN

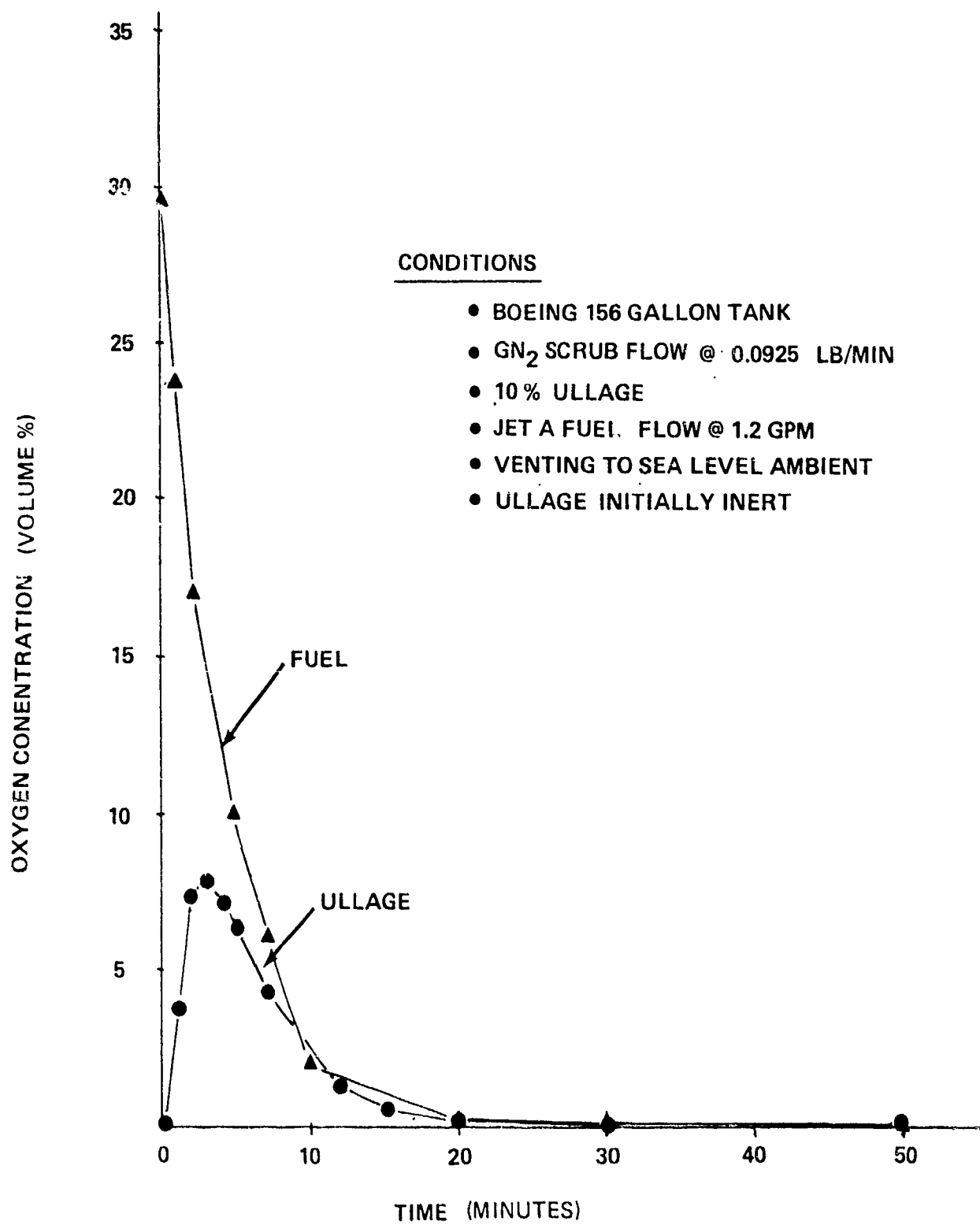


Figure 11 Measured Ullage and Fuel Oxygen Concentrations
Using GN_2 at 0.0925 LB/MIN with Initially Inert Ullage

3.0 FUEL SCRUB NOZZLE PERFORMANCE DURING SIMULATED MISSIONS

The performance of the C-5A scrub nozzle during simulated missions conducted in the SAFTE facility is discussed in this section. Additional information on the SAFTE facility is available in Ref. 5.

3.1 SAFTE Facility

The SAFTE facility is composed of three basic subsystems: (1) the SAFTE tank, (2) associated conditioning and delivery systems, and (3) a control and data acquisition system.

3.1.1 SAFTE Tank

The tank simulator (Figures 12 and 13) was equipped to specifically study the effects of tank pressure, ullage volume, slosh/vibration/circulation, and fuel scrubbing on oxygen (O_2) evolution.

3.1.1.1 Tank Pressure Control

Tank pressures were controlled through two accumulation tanks; a 3 gallon tank to duplicate an airplane surge tank (or vent box) and a 30 gallon altitude pressure tank to simulate ambient pressures. The tank and interconnecting plumbing are shown in Figure 14.

During the simulated climb, the altitude pressure tank was evacuated to the desired pressure with a vacuum pump (Figure 14, (A)). The altitude tank was plumbed directly to the surge tank (B) and the SAFTE tank ullage (C). A pressure transducer on the altitude tank provided feedback control (D) to the vacuum pump motor.

3.1.1.2 Tank Ullage Volume Control

Ullage volume was controlled by using a rate and totaling flow meter on the tank fuel discharge line (Figure 15, (A)). The constant speed fuel discharge pump (B) was controlled by throttling the pump discharge through a downstream proportional valve (C).

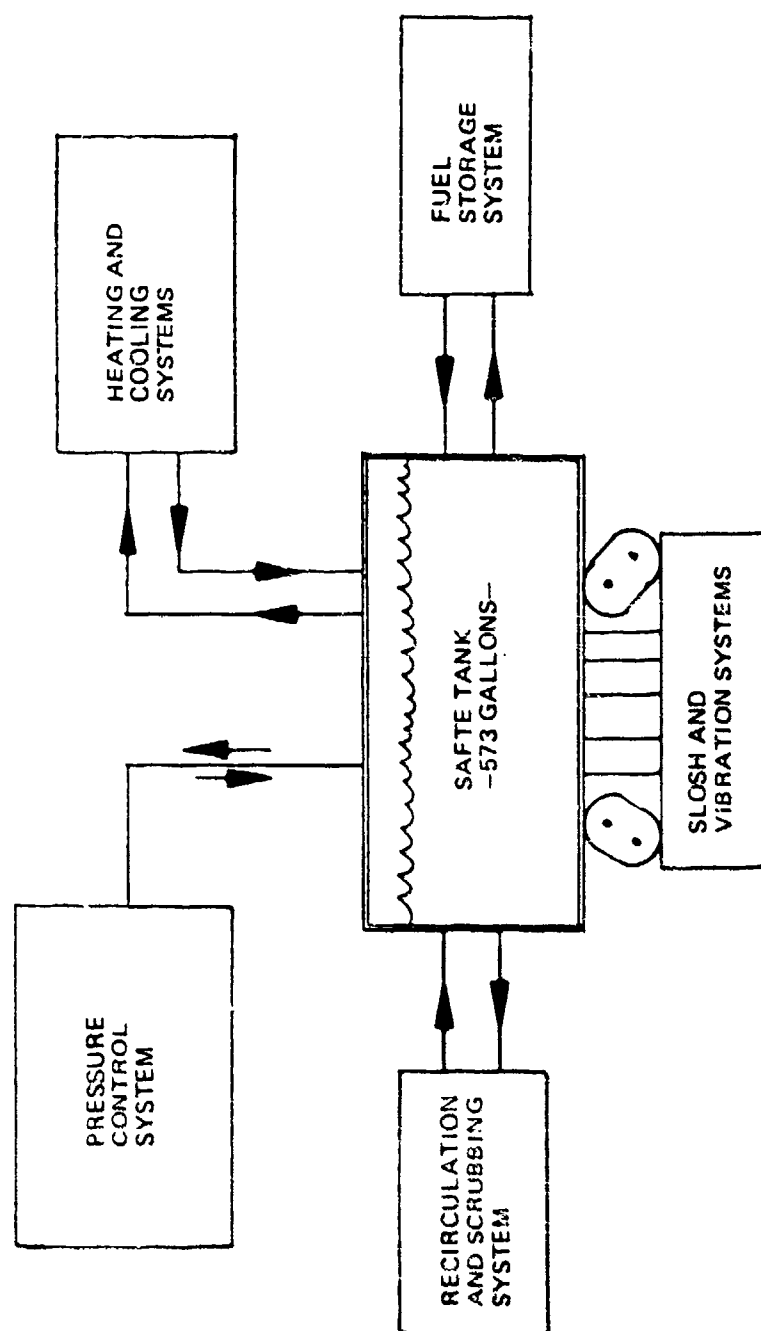


Figure 12. Functional Block Diagram of the Simulated Aircraft Fuel Tank Environment (SAFTE) Facility

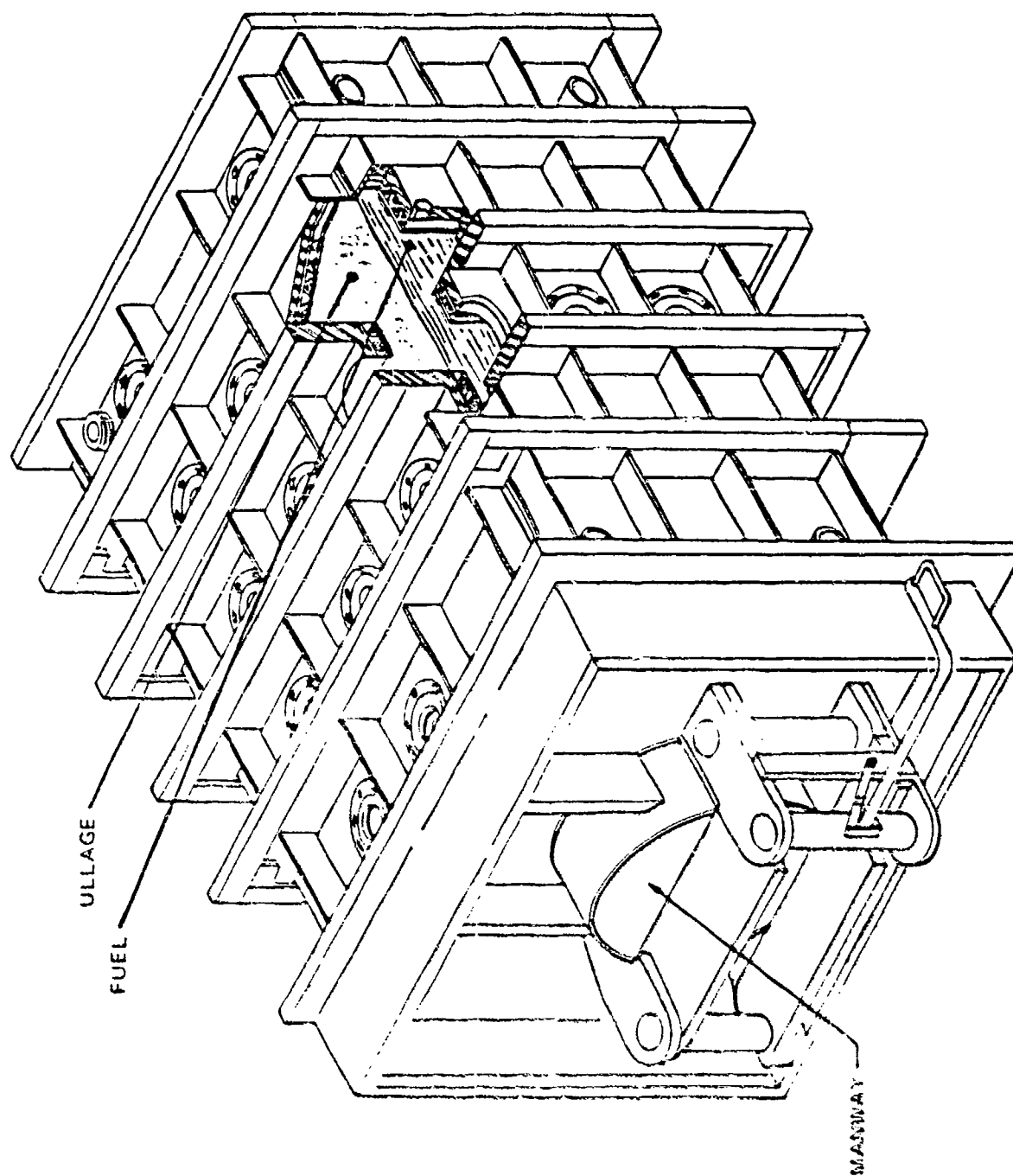


Figure 13. Diagram of SAFTE Tank Used in the Gas Evolution Tests

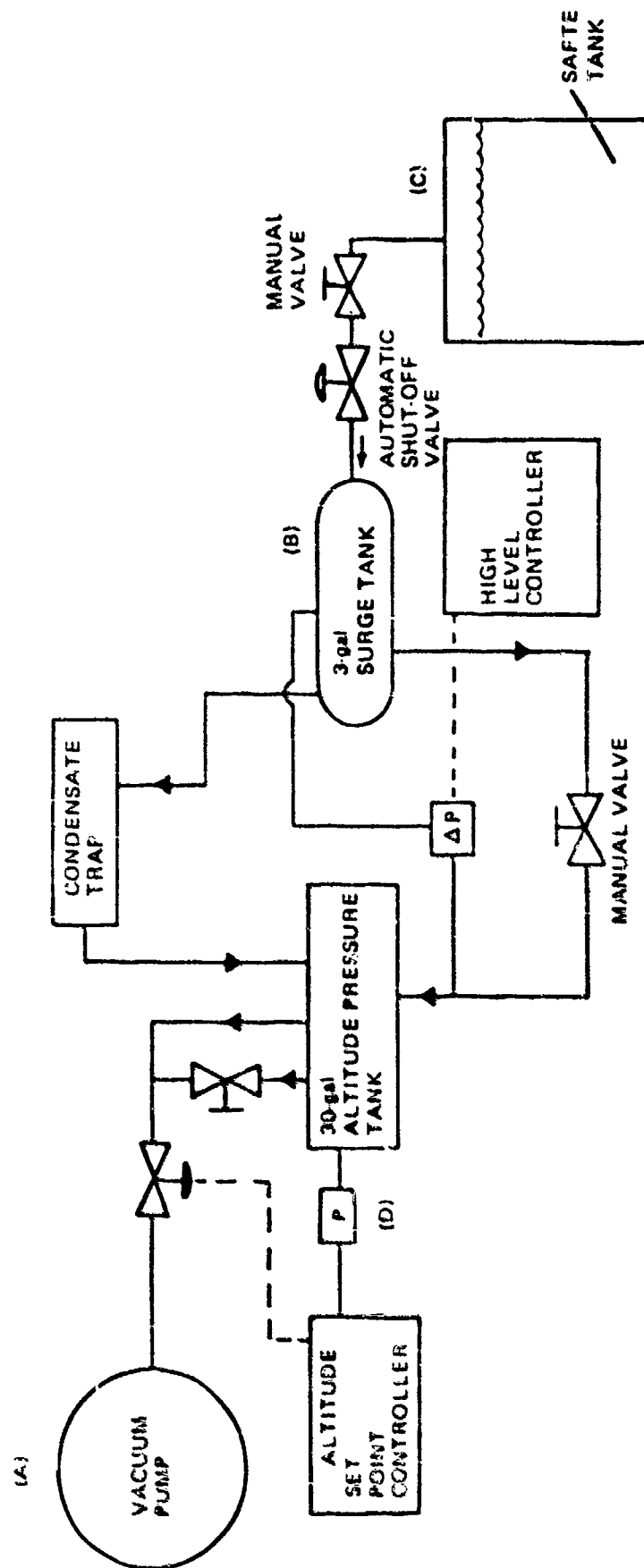


Figure 14 . Pressure Control System Schematic for the SAFTE Tank

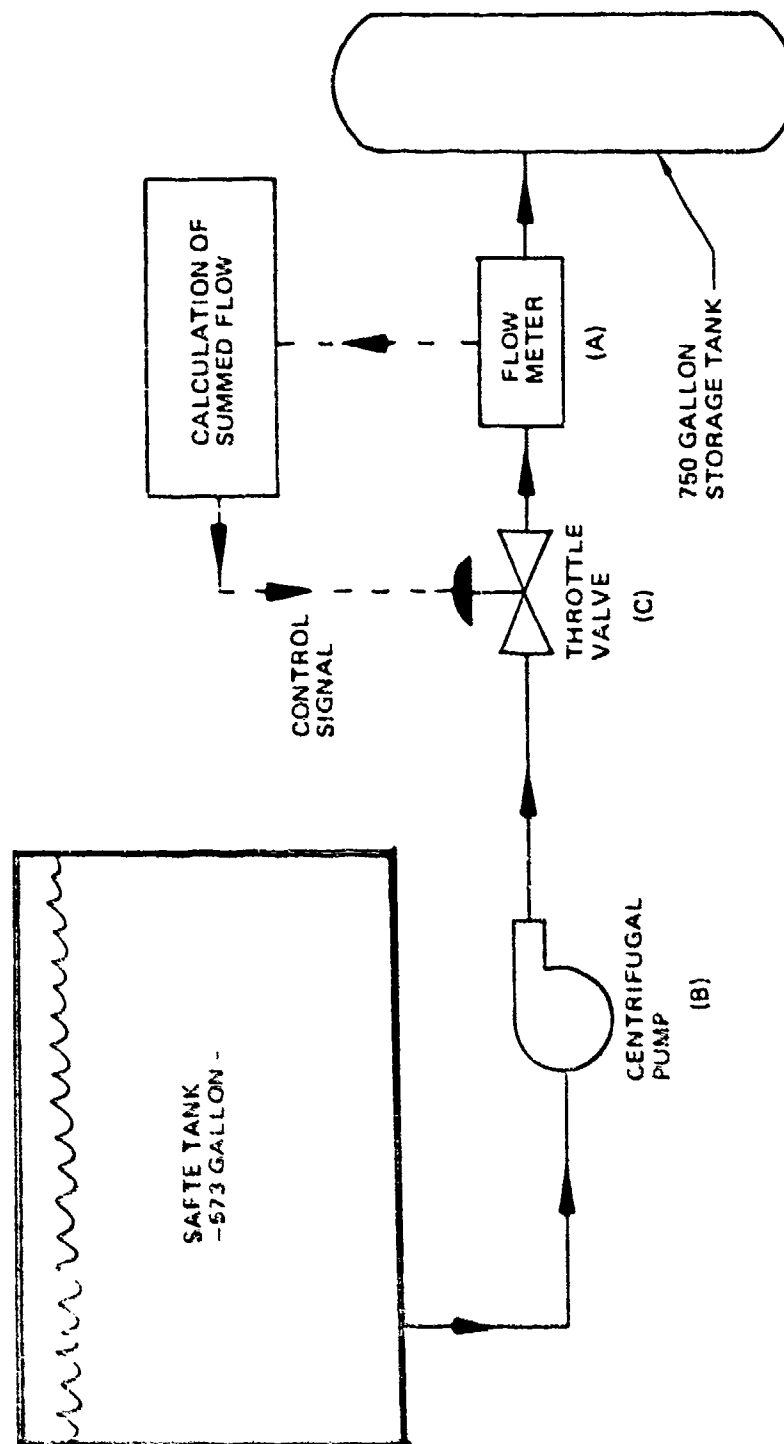


Figure 15. Ullage Volume Control System Schematic for the SAFTE Tank

3.1.1.3 Tank Slosh and Vibration Control

The SAFTE tank was installed on a slosh and vibration table (Figure 16) to simulate in-flight tank motion. The vibration frequency tested was at 50 Hz, with a maximum displacement within the tank of 0.01 inches (± 0.005 inches).

3.1.1.4 Fuel Circulation

Several recirculation currents may be found in most airplane fuel systems, and this added fuel motion will impact the dynamics of gas evolution. In the SAFTE tank, fuel was circulated through the centrifugal discharge pump (Figure 17, (A)) and the C-5A scrub nozzle (B). The nozzle was run with fuel only for the fuel recirculation tests.

3.1.1.5 Fuel Scrubbing System

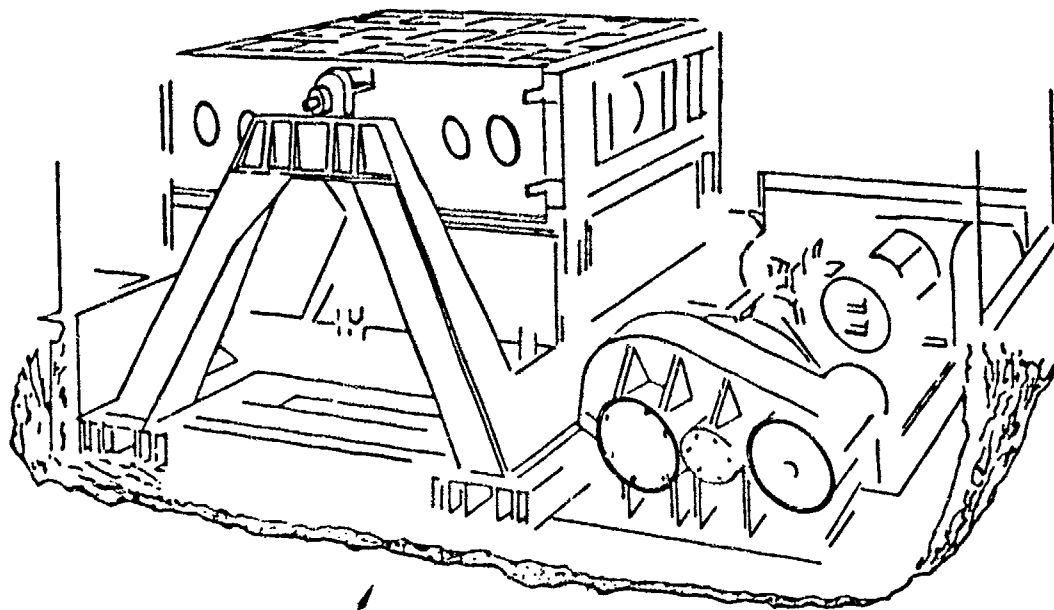
Fuel scrubbing was accomplished with the circulation pump (Figure 17, (A)), the C-5A nozzle (B) and an inert gas supply stream (C). Both fuel and gas flow rates were monitored with in-line flow meters.

3.1.2 Service Delivery Systems for the SAFTE Tank

The service delivery systems included systems for inert product gas flow using a mixing valve, process temperature control, and fuel delivery and discharge.

3.1.2.1 Mixing Valve/Inert Product Gas Delivery System

Inert gas was delivered to the fuel scrubbing system (Section 3.1.1.5) from two stored gas systems, air and gaseous nitrogen (GN_2), using a mixing valve (Figure 13). At the inlet to the mixing valve, both air and nitrogen flows were controlled to 0.3 pounds per minute and 50 psig. This system permitted accurate control of the mixing process to achieve the desired air/nitrogen blend. The nominal was nitrogen enriched air with oxygen concentration of 5% by volume (NEA_5) at a flow rate of 0.1 pounds per minute.



SAFTE TANK SHOWING
SLOSH MECHANISM

VIBRATION TABLE FOR
THE SAFTE TANK

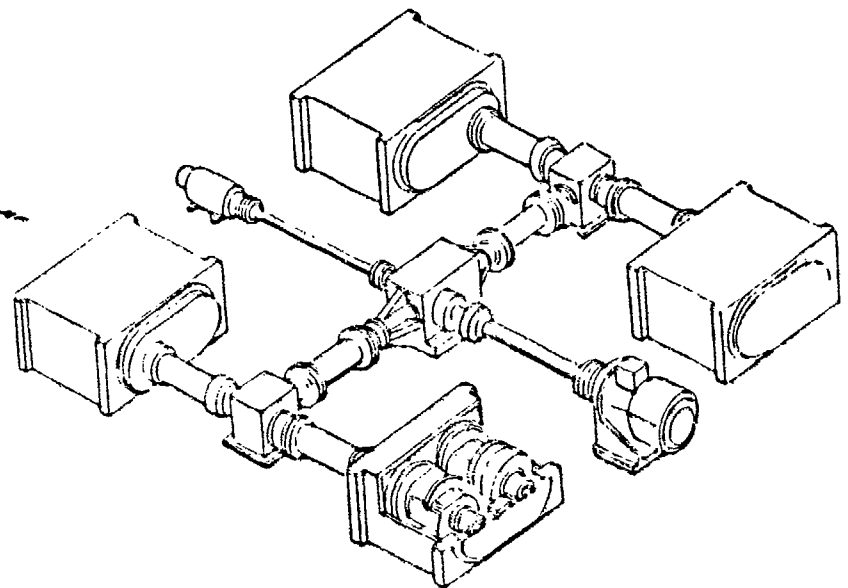


Figure 16. Slosh and Vibration Table for the SAFTE Tank

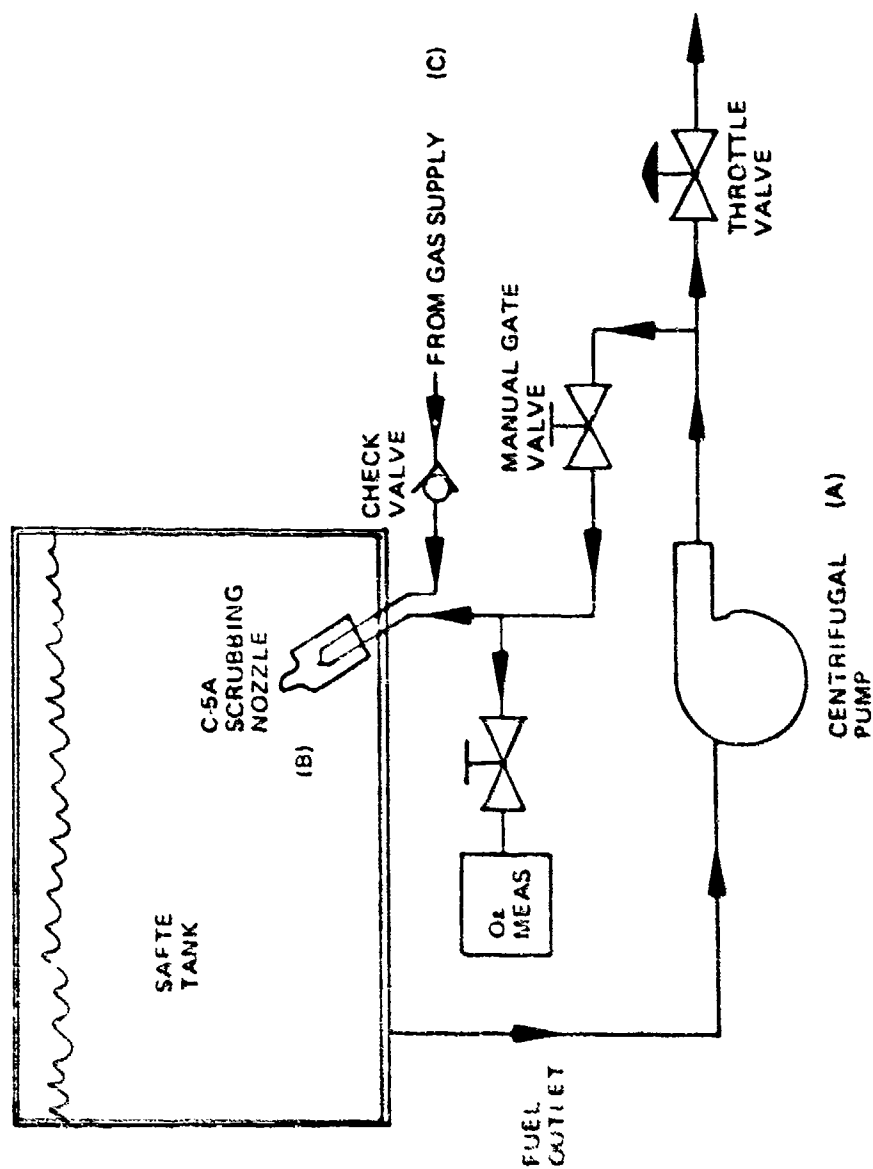


Figure 17. Fuel Circulation System Schematic for the SAFTE Tank

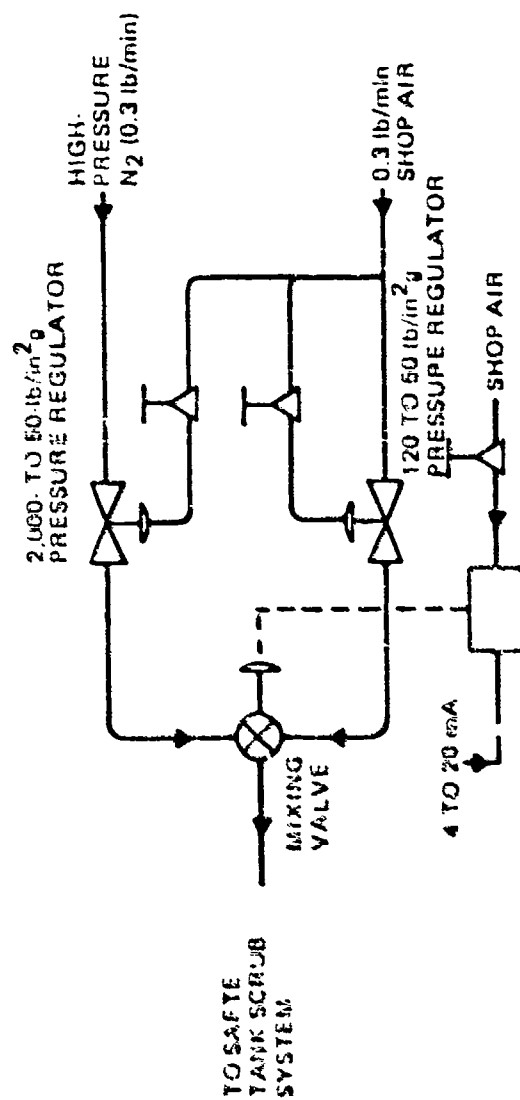


Figure 18. Mixing Valve Inert Gas Delivery System for the SAFTE Tank

3.1.2.2 Temperature Control System

The upper tank wall and the fuel temperatures were maintained at the 59°F nominal set point by means of inner wall heat transfer panels connected to a process temperature control system within Building 71B. This set-up is illustrated in Figure 19. Further details are available in Reference 5.

2.1.2.3 Fuel Delivery and Discharge

In this test series, the fuel sample was stored and reused after each run. The fuel storage and delivery system, illustrated in Figure 20, consisted of a storage tank, pressure relief valves, and 50 psig nitrogen pressure delivery system. The storage tank capacity was 750 gallons.

3.1.3 Instrumentation

Several tank variables were monitored for both control and monitoring functions. These included:

- o tank wall, ullage, and fuel temperature;
- o tank pressures for the SAFTE and altitude pressure tanks;
- o tank ullage O_2 and hydrocarbon concentrations;
- o concentration of fuel dissolved O_2 ; and
- o fuel flow rate and tank fuel volume.

A summary of the instrumentation used is described in Table 1. A more detailed description is given below.

3.1.3.1 Temperature Instrumentation

Temperature measurements were taken for the SAFTE tank wall, ullage, and the fuel. The tank top wall and fuel temperatures were controlled to a nominal 59°F. Measurements of the fuel and ullage temperatures were taken with sheathed Type K thermocouples while tank surface measurements were made with Type K thermocouple wires bonded to the metal surface.

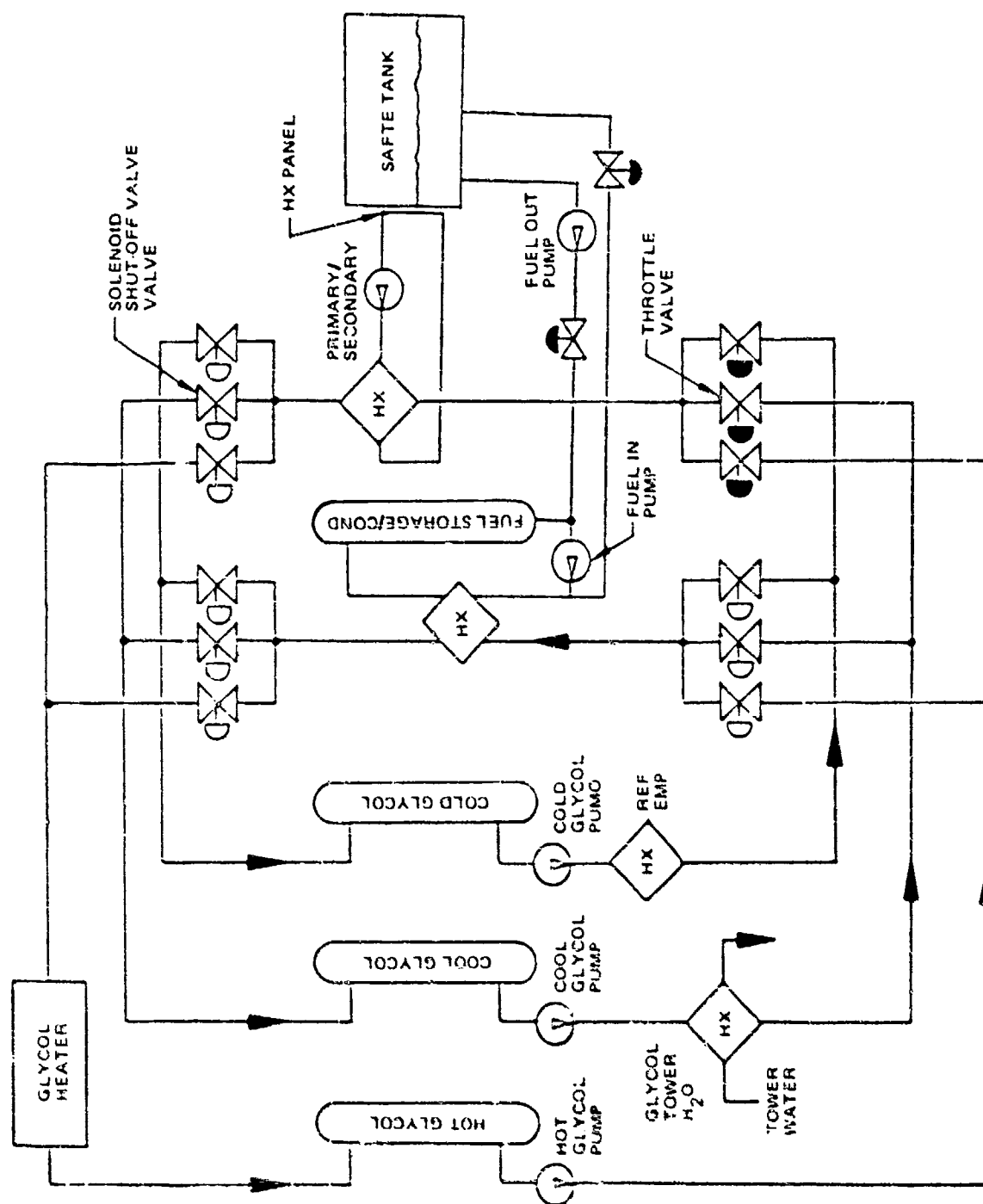


Figure 19. Temperature Control System Schematic for the SAFTE Tank

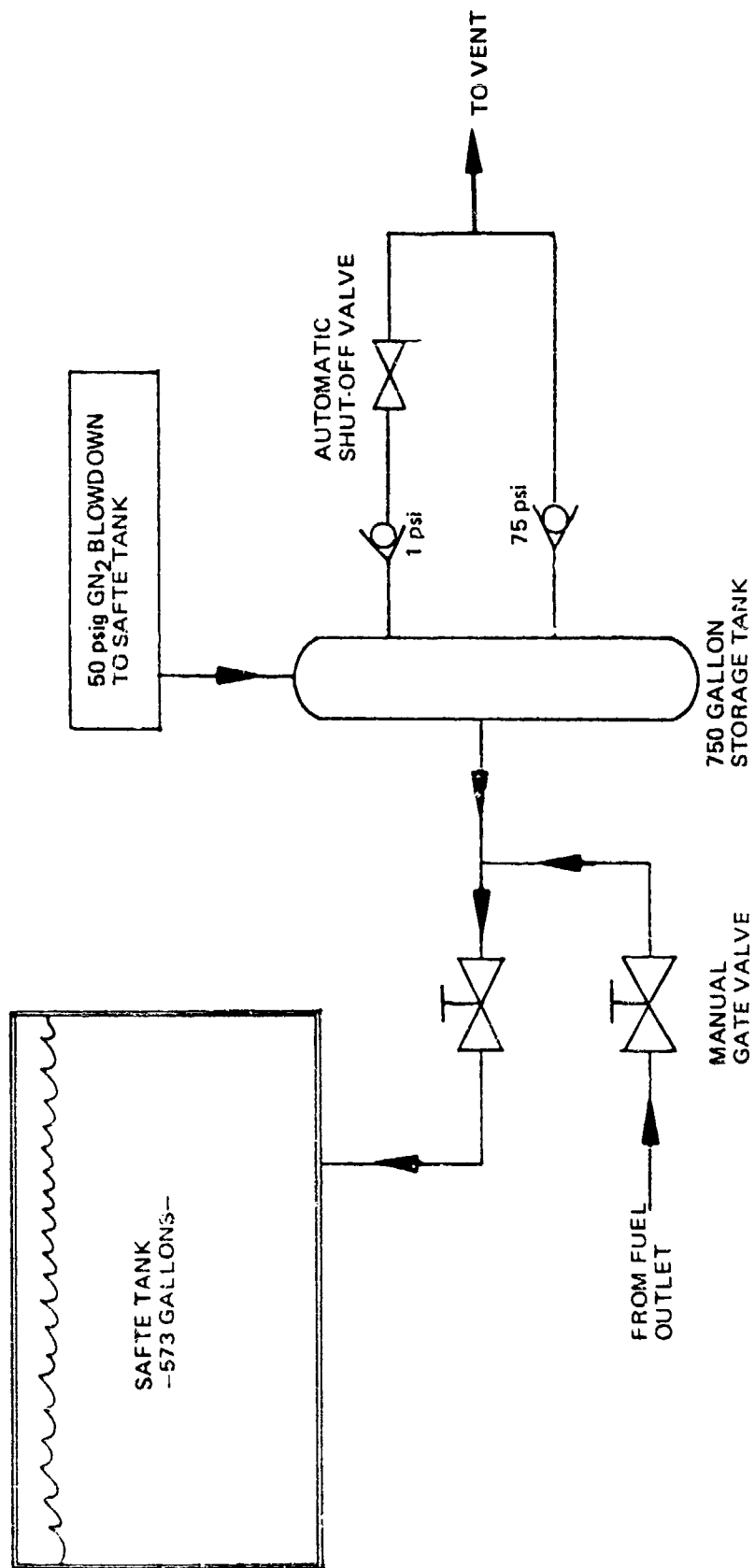


Figure 20. Fuel Storage and Delivery System Schematic for the SAFTE Tank

TABLE 1
INSTRUMENTATION FOR THE O₂ EVOLUTION TESTS IN THE SAFTE FACILITY

MEASUREMENT FUNCTION	COMPONENT	TYPE	RANGE	DESIGNATION
VESSEL PRESSURE	ALTITUDE TANK	PSIA TRANSDUCER	0-14.7 PSIA	PT-101
VESSEL PRESSURE	SURGE TANK	PSID TRANSDUCER	-10.0 - + 10 PSID	AP-305
FUEL DISSOLVED O ₂ CONCENTRATION	SAFTE TANK	BECKMAN MEMBRANE ANALYZER	0-100%	O ₂ -302
WALL TEMPERATURE	SAFTE TANK	TYPE J - TC	-40° - 120°F	-----
ULLAGE TEMPERATURE	SAFTE ULLAGE	TYPE J - TC	-40° - 120°F	-----
FUEL TEMPERATURE	SAFTE TANK	TYPE J - TC	-40° - 120°F	-----
FUEL FLOW RATE	SAFTE OUTLET	GPM FLOWMETER	0-3 GPM	-----
FUEL EXPENDED	SAFTE TANK	FLOWMETER SUM	0-573 GAL	-----
PROBE POSITION	SAFTE TANK ULLAGE	POTENTIOMETER	0-1000 mm	-----
ULLAGE O ₂ CONCENTRATION	SAFTE TANK ULLAGE	MASS SPECTROMETER	0-20.9%	-----
ULLAGE HC CONCENTRATION	SAFTE TANK ULLAGE	MASS SPECTROMETER	0-100%	-----
INERT GAS CONCENTRATION	MIXING VALVE OUTLET	BECKMAN MEMBRANE ANALYZER	0-20.9%	O ₂ -301

3.1.3.2 Tank Pressure Instrumentation

The principal pressure measurements were made in the tank ullage and in the vent surge tank. The altitude tank was controlled to either constant sea level flight or to a simulated KC-135 mission climb. In this arrangement, the pressure in the SAFTE tank was controlled indirectly by the surge tank.

3.1.3.3 Gas Concentration Instrumentation

Ullage gas concentrations were measured to determine the relative flammability of the ullage under the test conditions evaluated. Ullage O_2 concentration levels and hydrocarbon concentrations were measured using a mass spectrometer.

Ullage measurements were made in three locations - near the tank top-wall (probe 1), at ullage center (probe 2), and near the fuel surface (probe 3)-by means of a sensor probe positioning system (hydraulically actuated) mounted at the tank top. The probe positions were adjusted in the ullage automatically to conform to expansion due to fuel depletion. The positioning system is shown in the diagram of Figure 21. Specific probe locations in the SAFTE tank are shown in Figure 22 for the two ullage sizes used in this test.

3.1.3.4 Fuel Dissolved Oxygen Concentration

The mass spectrometer was used to measure the amount of O_2 dissolved in the fuel by sampling fuel passing through the fuel circulation system.

3.1.3.5 Tank Fuel Volume Control

Fuel (and ullage) volumes were measured indirectly using a turbine flowmeter and integrating the output. Fuel volume control was necessary to simulate the KC-135 fuel depletion schedule. Data from the ullage volume reading was also used to automatically position the ullage concentration probes as the test proceeded.

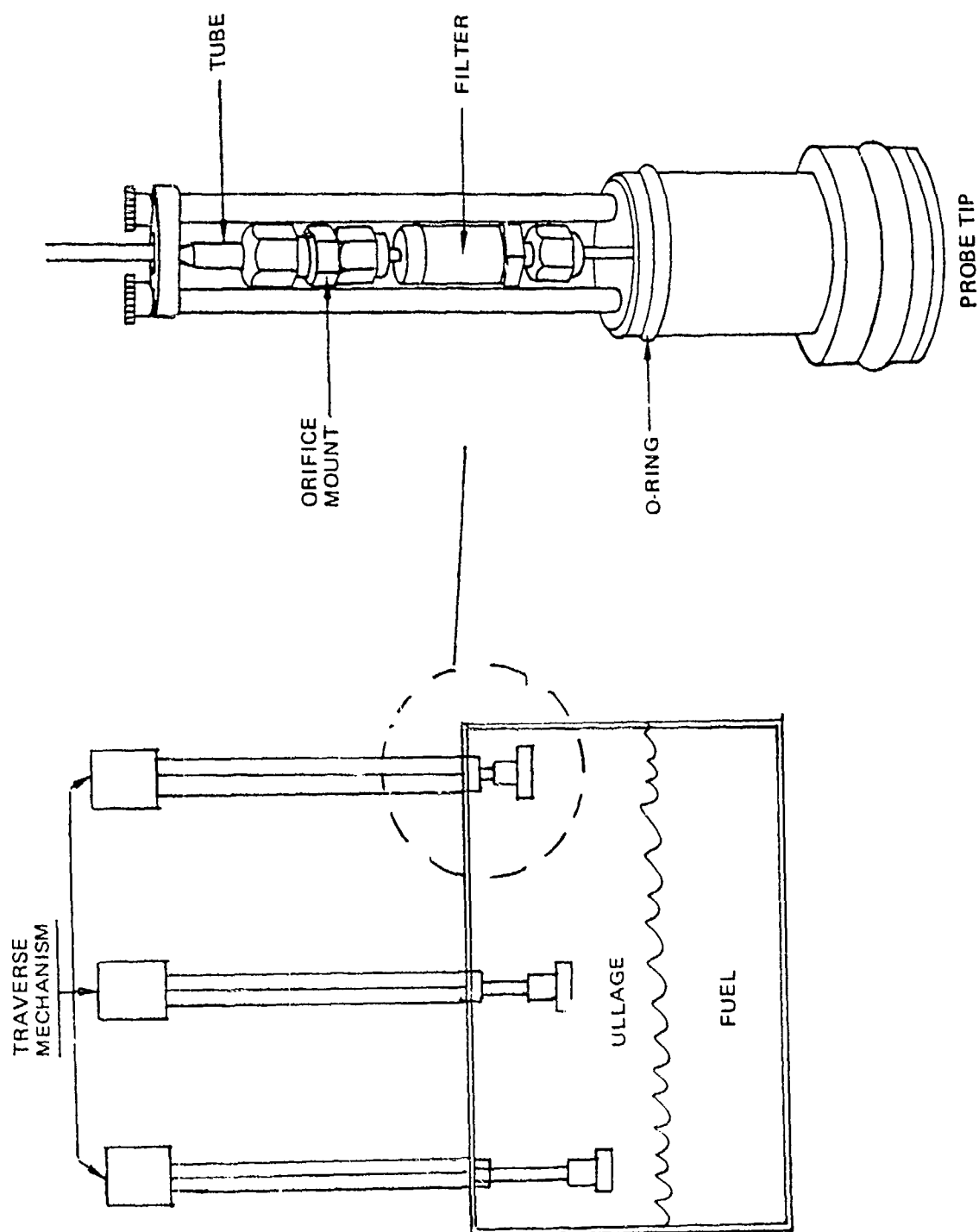


Figure 21. Diagram of Ullage Probe Positioning System in the SAFTE Tank

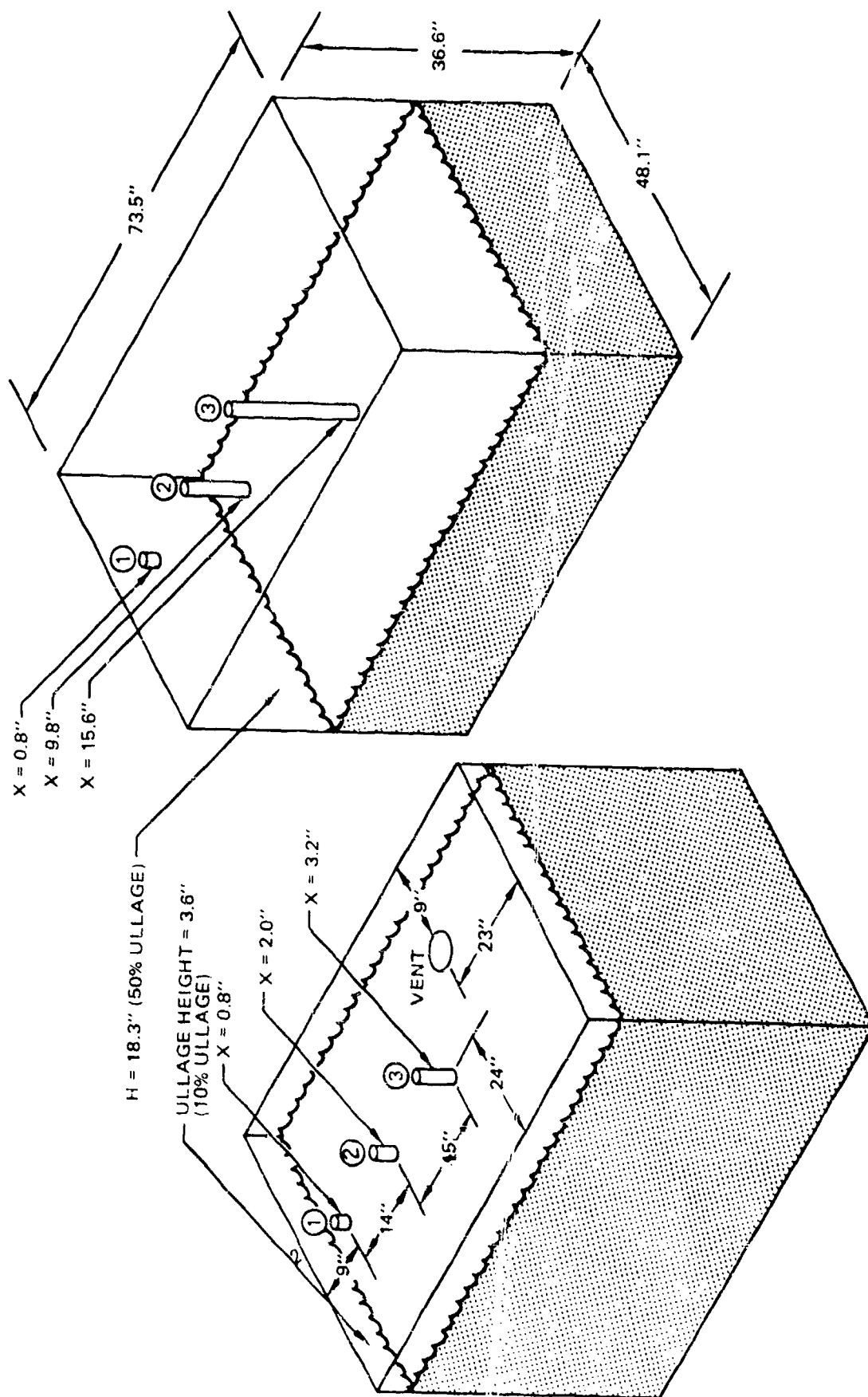


Figure 22 . Probe Positions for the SAFTE Tank

3.2 Test Procedures

Tests were performed in three main categories during this test period: tests at constant volume and constant pressure, simulated climb tests at constant volume, and KC-135 mission simulation tests (including fuel burn).

Several test conditions were common to all three categories to ensure maximum experimental control and repeatability. These common conditions included:

- o The SAFTE tank was vented to the simulated altitude ambient pressure. (No climb or dive valves were used).
- o The oxygen concentration of the inert gas was 5% by volume with a scrub flow rate of 0.1 lb/minute.
- o Top wall and fuel bulk temperatures were controlled to 59°F (nominal).
- o The air flowed through the scrub nozzle to saturate the fuel within 90% of the equilibrium dissolved O_2 saturation concentration ($\approx 35\%$).
- o The fuel type was JP-4.
- o Initial ullage O_2 concentrations were set to $5\% \pm 2\%$ by washing the initial ullage volume with nitrogen enriched air with 5% oxygen (NEA_5). The mission simulation was started shortly thereafter.

The test matrix for the three test categories is shown in Table 2. Data for all the channels described in Table 1 were continuously recorded for each test.

3.2.1 Tests at Constant Volume and Constant Pressure

3.2.1.1 Test Setup

In this sequence the fuel depletion, slosh/vibration, and altitude pressure control systems were inactive. The fuel scrubbing system was used with NEA_5 and the in-tank scrub nozzle.

TABLE 2 TEST MATRIX FOR O₂ EVOLUTION TESTS IN THE SAFTE FACILITY-APRIL, 1983

CONDITION NUMBER	ULLAGE PRESSURE		ULLAGE VOLUME		INITIAL ULLAGE		SCRUB FLOW			VIBRATION	COMMENTS
	CONSTANT	SIMULATED CLIMB	CONSTANT	KC-135 SCHEDULE	10%	50%	NONE	0.1PPM NEAS	CIRCULATION ONLY		
11	■		■		■				■		BASELINE FOR CONSTANT PRESSURE/VOLUME TESTS EFFECT OF INITIAL VOLUME
12	■		■			■			■		
21		■	■		■				■		BASELINE FOR CONSTANT VOLUME CLIMB SIMULATION EFFECT OF INITIAL VOLUME EFFECT OF SCRUB FLOW EFFECT OF VIBRATION EFFECT OF FUEL CIRCULATION EFFECT OF CIRCULATION & VIBRATION
22		■	■			■			■		
23		■	■		■		■				
24		■	■		■		■		■	■	
25		■	■		■		■		■	■	
26		■	■		■		■		■	■	
31		■		■	■				■		BASELINE KC-135 SIMULATION EFFECT OF INITIAL VOLUME
32		■		■		■			■		

3.2.1.2 Test Sequence

The following sequence was used for the constant volume/pressure tests:

Run 1.1

- o Test tank was filled with 516 gallons of JP-4 fuel (10% ullage).
- o Air was bubbled through the fuel using the in-tank scrub nozzle for approximately 1 hour.
- o The ullage was washed with NEA₅ for approximately 5 minutes.
- o Immediately after the washing period, the scrubbing system was activated with 0.1 pounds per minute scrub gas flow and approximately 2.4 gallons per minute fuel flow.
- o Scrubbing continued until the ullage O₂ concentration dropped to 5% and was maintained at or below 5% for several minutes.

Run 1.2

- o The tank was filled with 291 gallons of JP-4 (50% ullage).
- o Air was bubbled through the fuel and scrubbing was activated as before.

3.2.2 Simulated Climb Tests at Constant Volume

In these tests, the tank pressure control, fuel scrubbing, tank temperature, fuel circulation, and slosh and vibration systems were active while the fuel depletion system was not. The following sequence was observed:

- o Tank was filled to 10% ullage and aerated as before (one run was made with a 50% ullage).

- o Tank pressure (or equivalent altitude tank pressure) was controlled to the climb pressure schedule shown in Figure 23, reflecting the ascent rate for a KC-135.
- o Scrubbing, circulation, and slosh and vibration were selectively activated during the simulated climb exercise. The fuel circulation rate was 2.5 gallons per minute, and the vibration level tested was 0.01 inches double amplitude at 50 Hz (corresponding to 1.3 G's).

3.2.3 Procedures for KC-135 Mission Simulation

This test was similar to the previous sequence in terms of preparation and simulated climb pressure control. In addition, fuel was depleted at a rate corresponding to the KC-135 climb fuel burn rate. Only the effect of initial ullage volume, 10% (516 gallons fuel) versus 50% (291 gallons fuel), was evaluated in this KC-135 simulation.

3.3 Results

3.3.1 Facility Performance Results

The control system for scrub gas mass flow rate, gas quality (a function of the mixing valve setting), tank wall and bulk fuel temperature, and tank pressure all performed satisfactorily and showed good repeatability between tests. Measurement results of tank pressure (during climb - Figure 23), fuel volume during depletion (Figure 24), inert gas quality (Figure 25), and tank temperature (Figure 26) indicated that the control systems performed as required. Tank skin and bulk fuel temperatures for all tests were controlled to within $\pm 3^{\circ}\text{F}$ of the 59°F setpoint.

3.3.2 Results of Tests at Constant Volume and Constant Pressure

Two important trends were noted from the constant volume/constant pressure test conditions:

- o With an ullage volume of 50% (ullage depth at 15.6 inches), the peak O_2 concentration measurement for any position in the ullage was

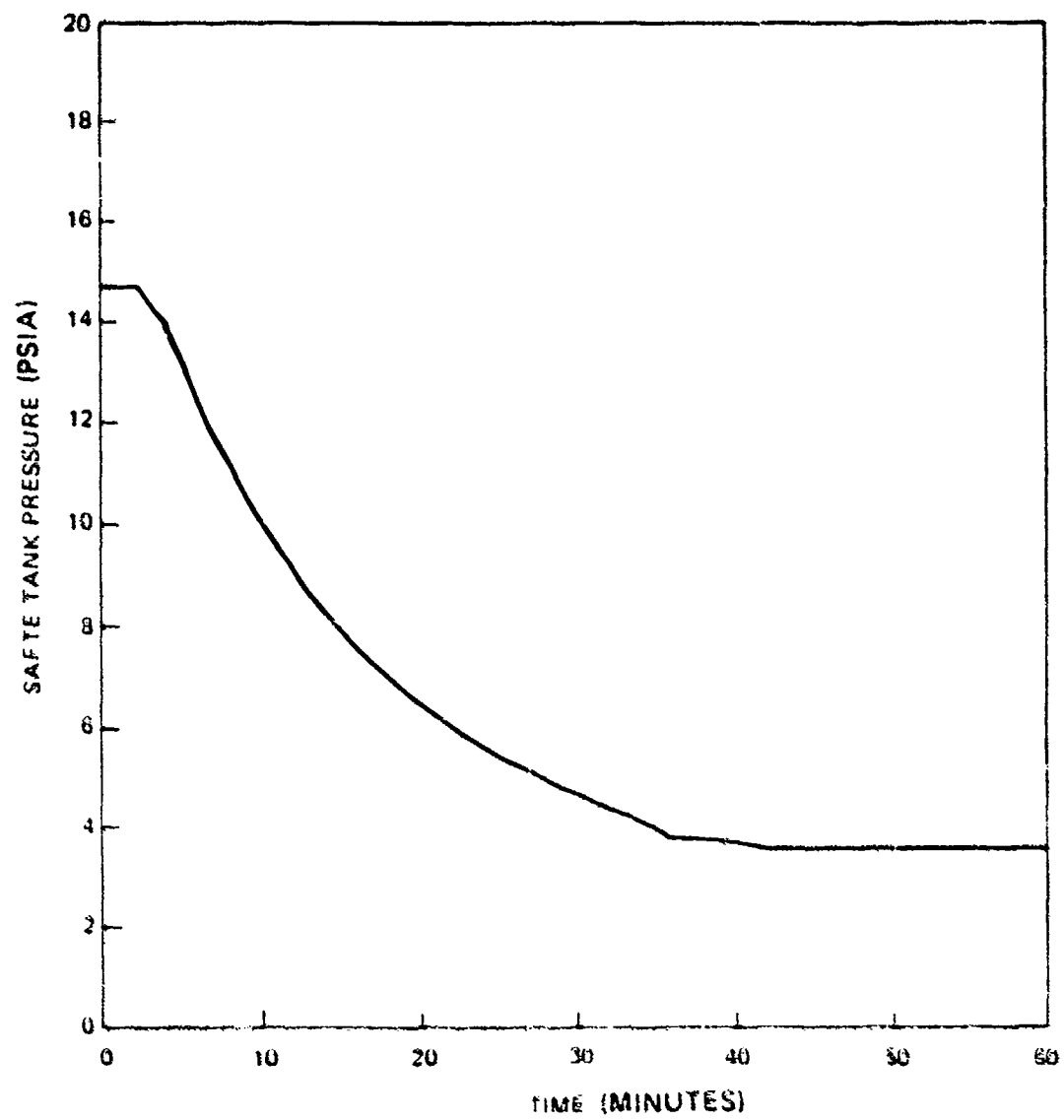


Figure 23. Tank Pressure Measurement for the Simulated KC 135 Climb

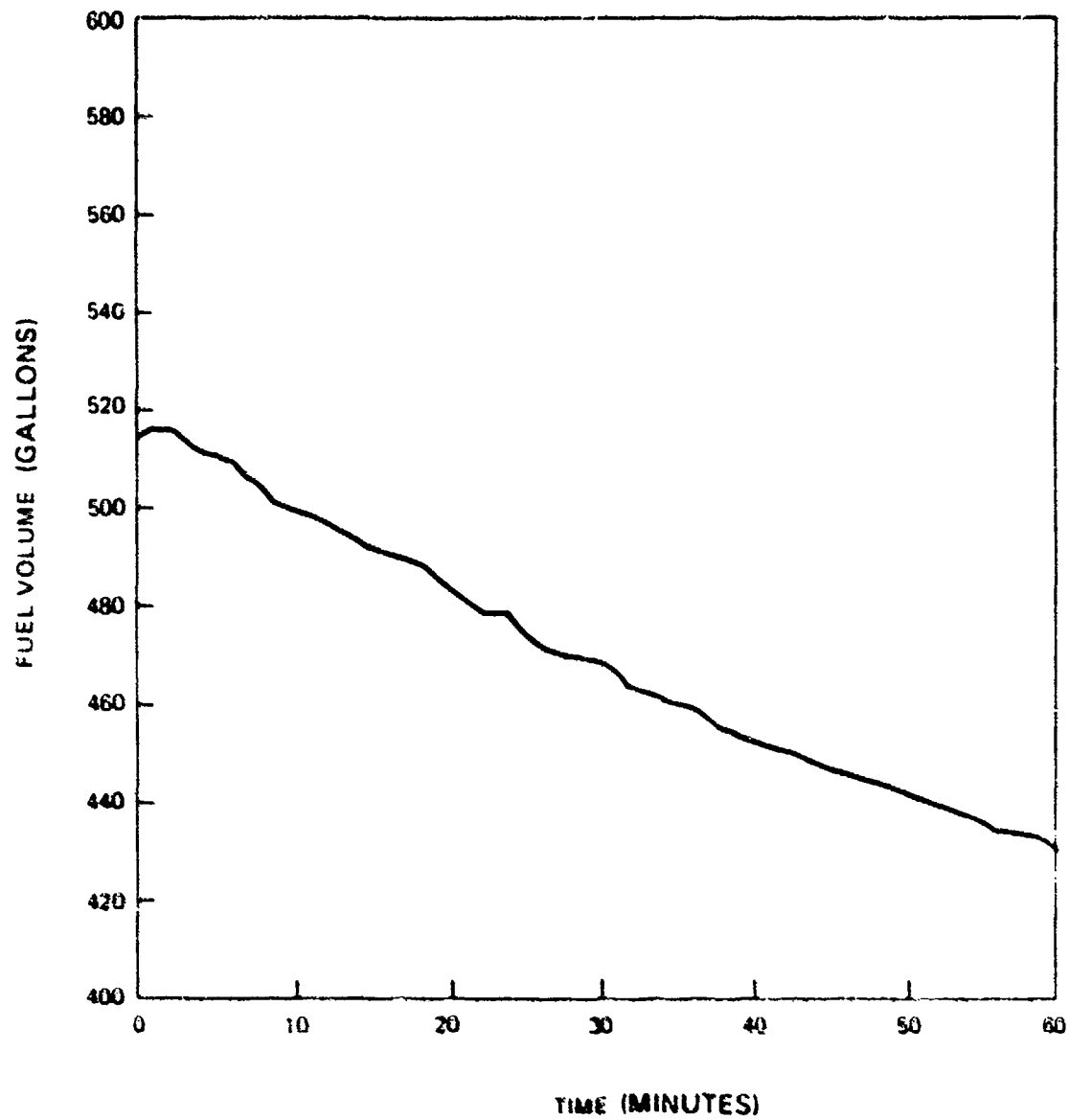


Figure 24 . Tank Volume Levels for Simulated KC-135 Fuel Depletion in the SAFTE Tank

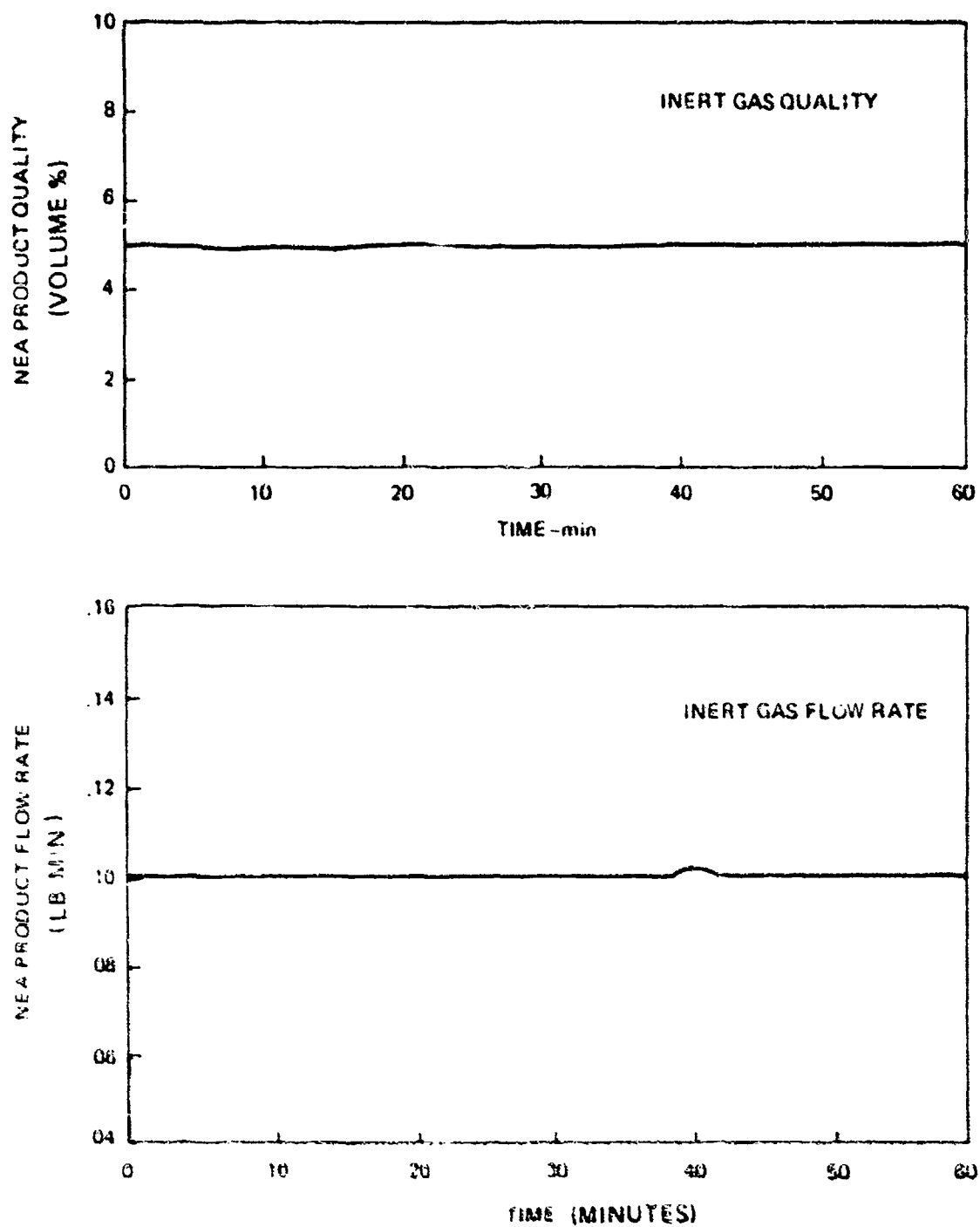


Figure 25 . Inert Gas Quality (Top) and Flow Rate Measurements for the Simulated SAFTE IGG System

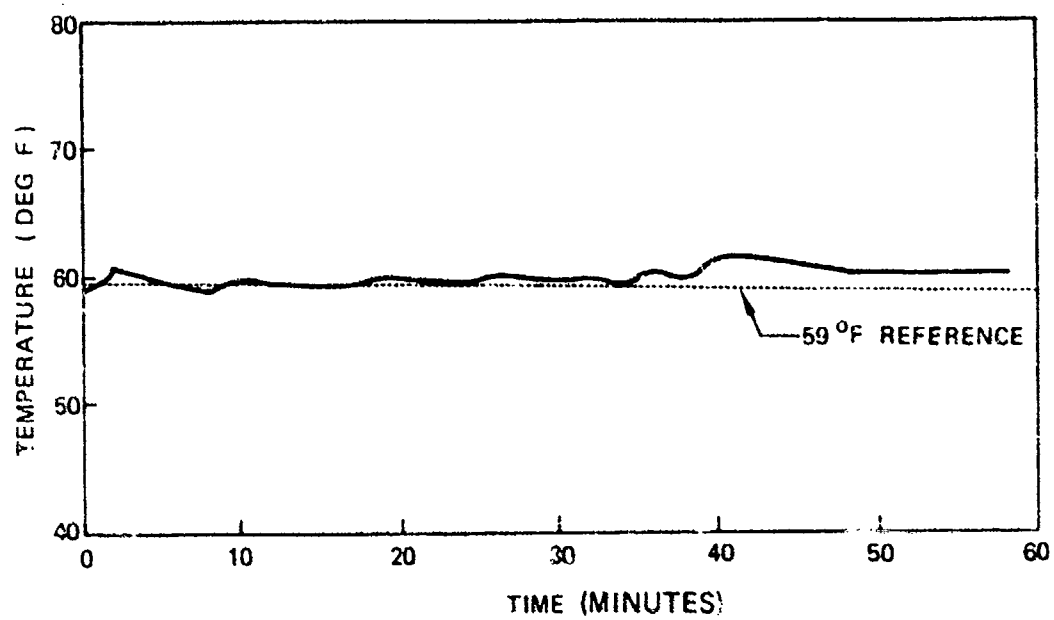


Figure 26 . Measured Fuel Temperatures for the SAFTE Tank

approximately 9% (NEA₅ scrub gas at 0.1 pounds per minute) compared to a peak O₂ concentration of 12% with an ullage volume of 10% (3-inch depth).

- o Significant stratification occurred with a 50% ullage volume during the first 15 minutes of scrubbing with an accumulation of oxygen and fuel vapor evident near the fuel surface. Conversely, little stratification was evident with a 10% ullage volume during the entire scrubbing interval.

The first trend is illustrated in Figure 27 which shows O₂ and hydrocarbon concentration values near mid-ullage with both the 50% and 10% ullage volumes.

Two factors affecting this trend seem to be: (1) more O₂ is available for release from the fuel with 10% ullage and (2) the smaller ullage is more sensitive to gas influx at a given rate than the larger ullage, noting that both ullages began at approximately a 4% O₂ concentration.

Evidence of stratification of evolved gas for the larger ullage is presented in Figure 28, which shows the measured O₂ and vapor concentration levels at three probe positions, 0.3 inch, 9.8 inches, and 15.6 inches from the tank top wall. In this test, the stratification was pronounced for the first 15 minutes; subsequently, ullage currents (probably due to the scrubbing process) were sufficiently strong to create a more well-stirred condition. In the 10% ullage case, there was less evidence of layering in the first 15 minutes (Figure 29).

3.3.3 Results of Constant Volume Climb Simulation

Several variables were evaluated including the effects of decreased tank pressure, vibration and circulation of fuel, fuel scrubbing, and initial ullage volume.

3.3.3.1 Effects of Initial Ullage Volume

As in the constant pressure test, ullage O₂ concentrations reached higher levels in the 10% ullage than in the 50% ullage as indicated by comparing the

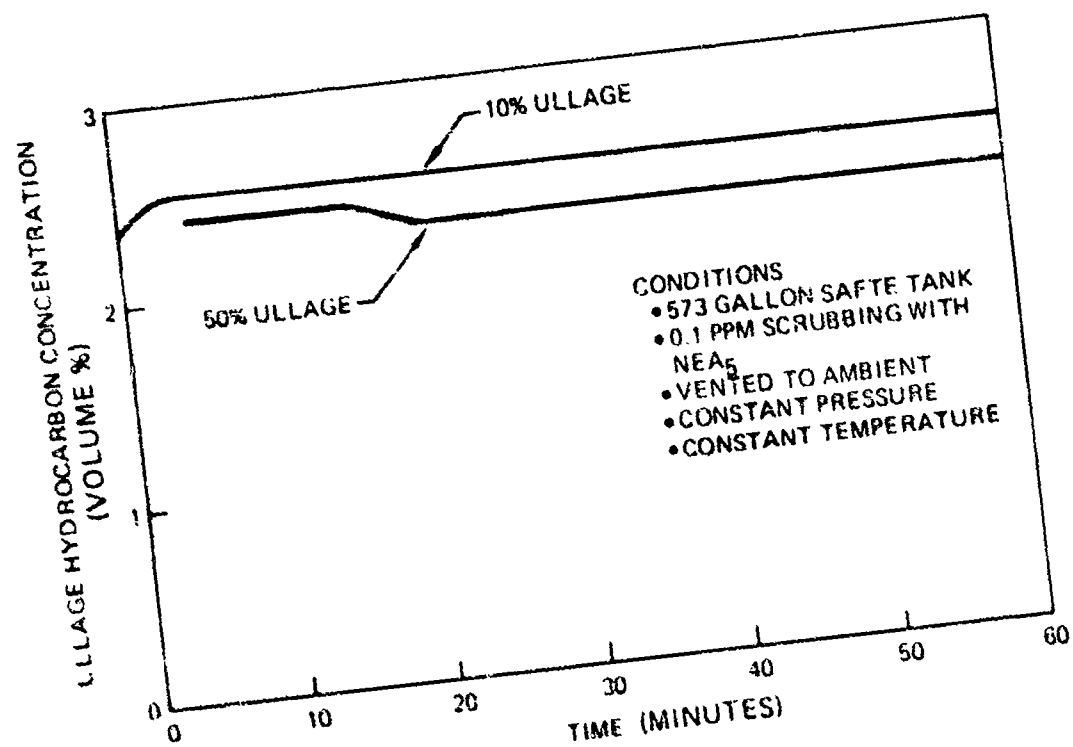
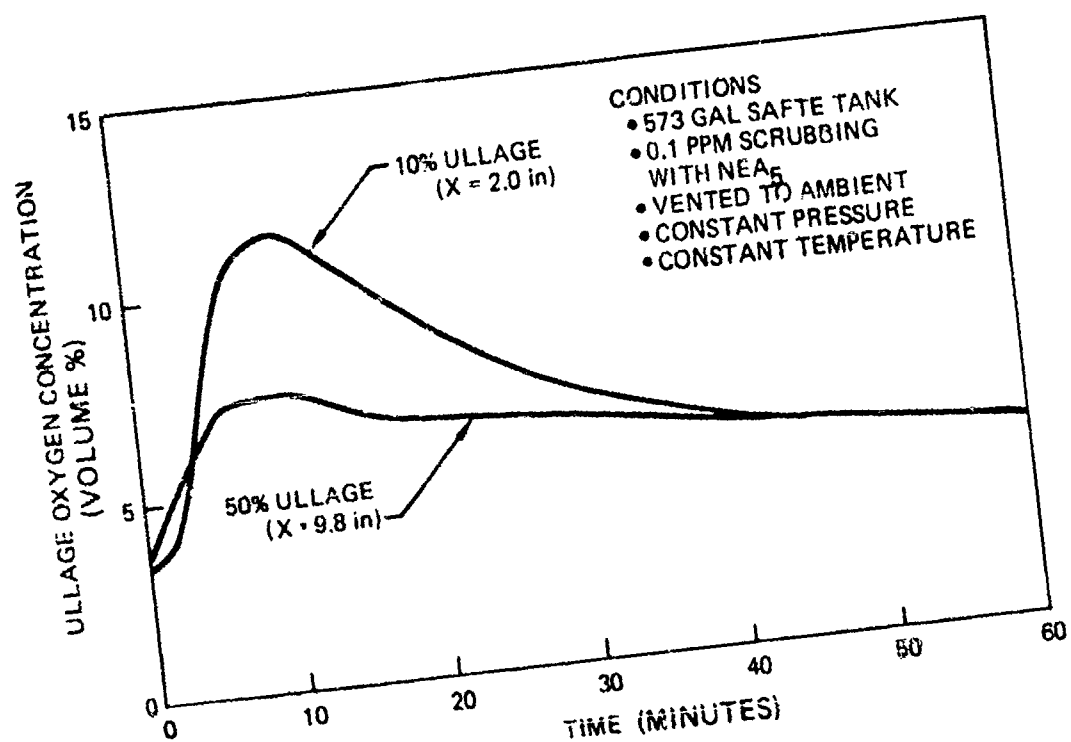


Figure 27. Mid-Ullage Oxygen and Fuel Vapor Concentrations for Constant Volume/Constant Pressure Scrubbing at 10% and 50% Ullage Volume

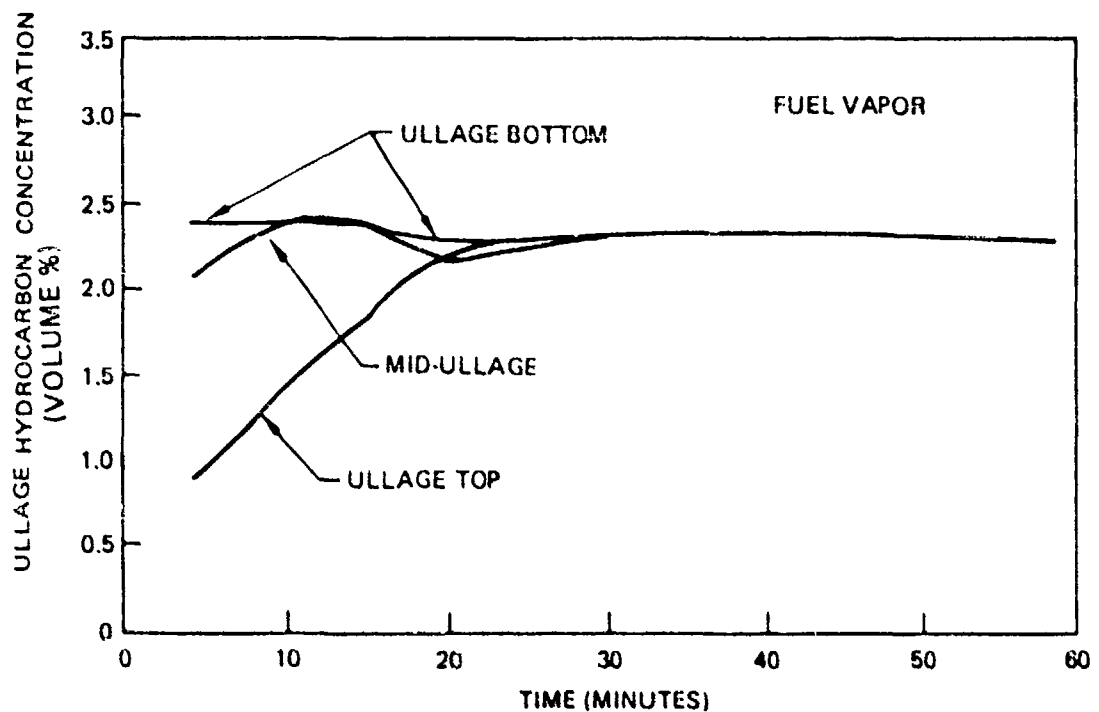
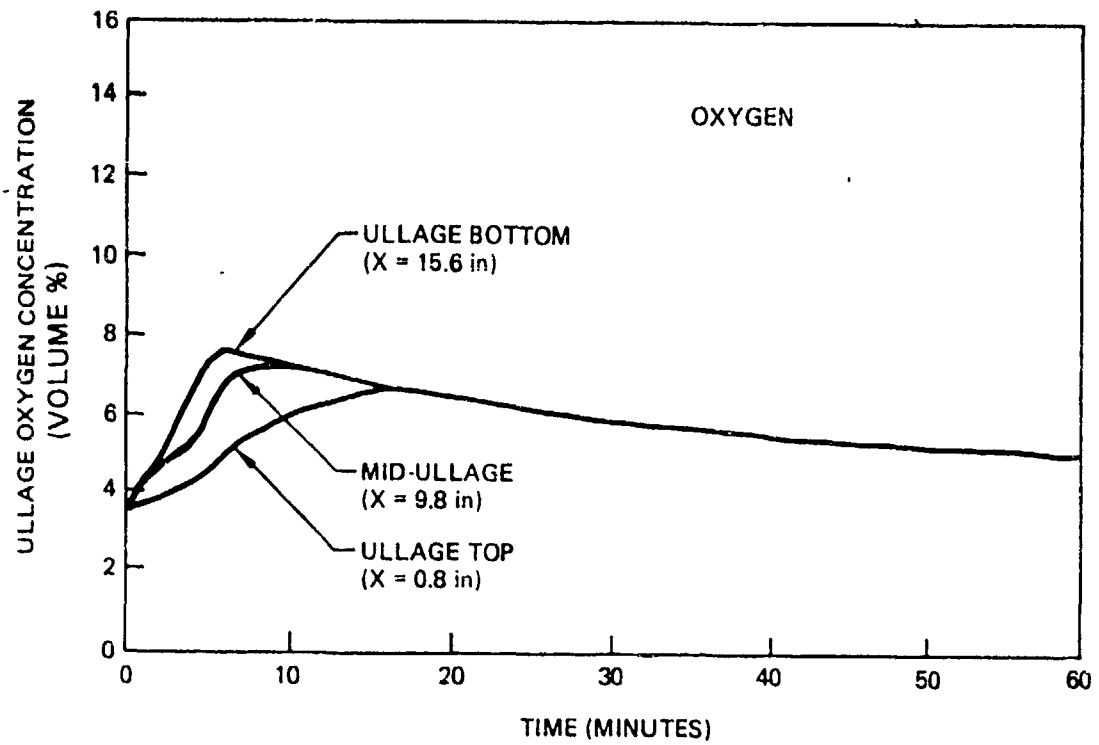


Figure 28 . Spatial Variations of Oxygen and Fuel Vapor Concentration for Constant Volume/Constant Pressure Scrubbing at 50% Ullage Volume

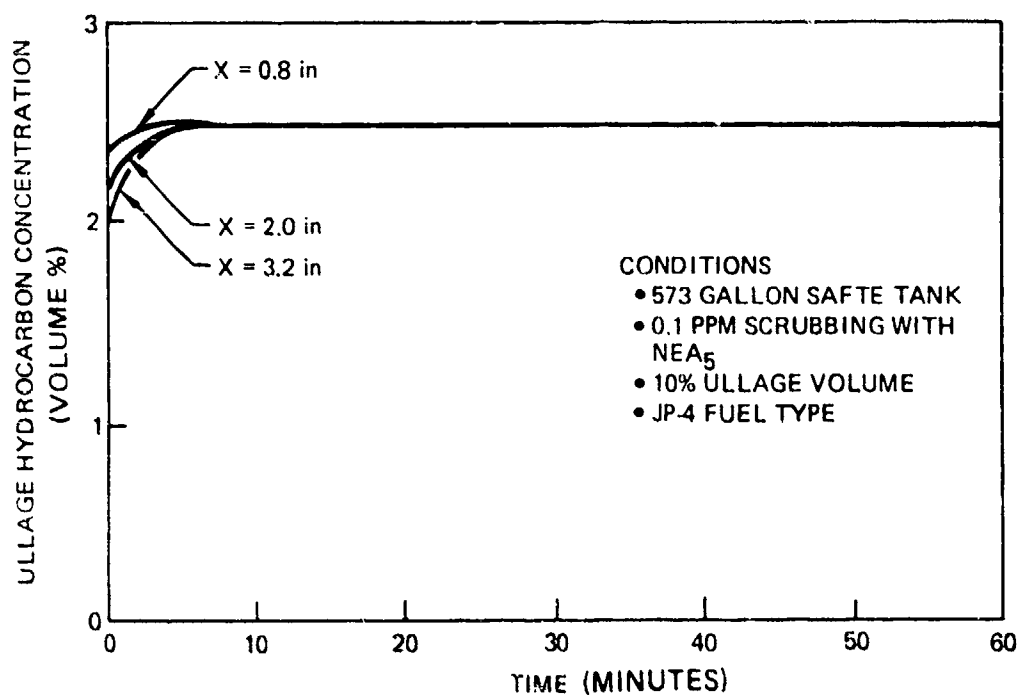
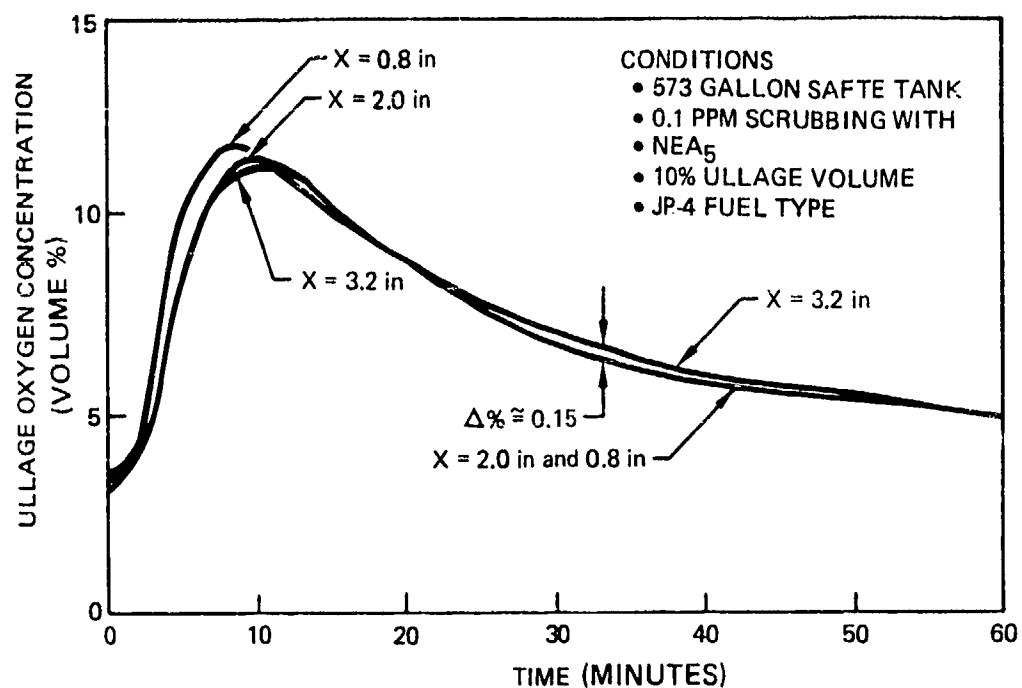


Figure 29. Spatial Variation of Oxygen and Fuel Vapor Concentrations for Constant Volume/Constant Pressure Scrubbing at 10% Ullage Volume

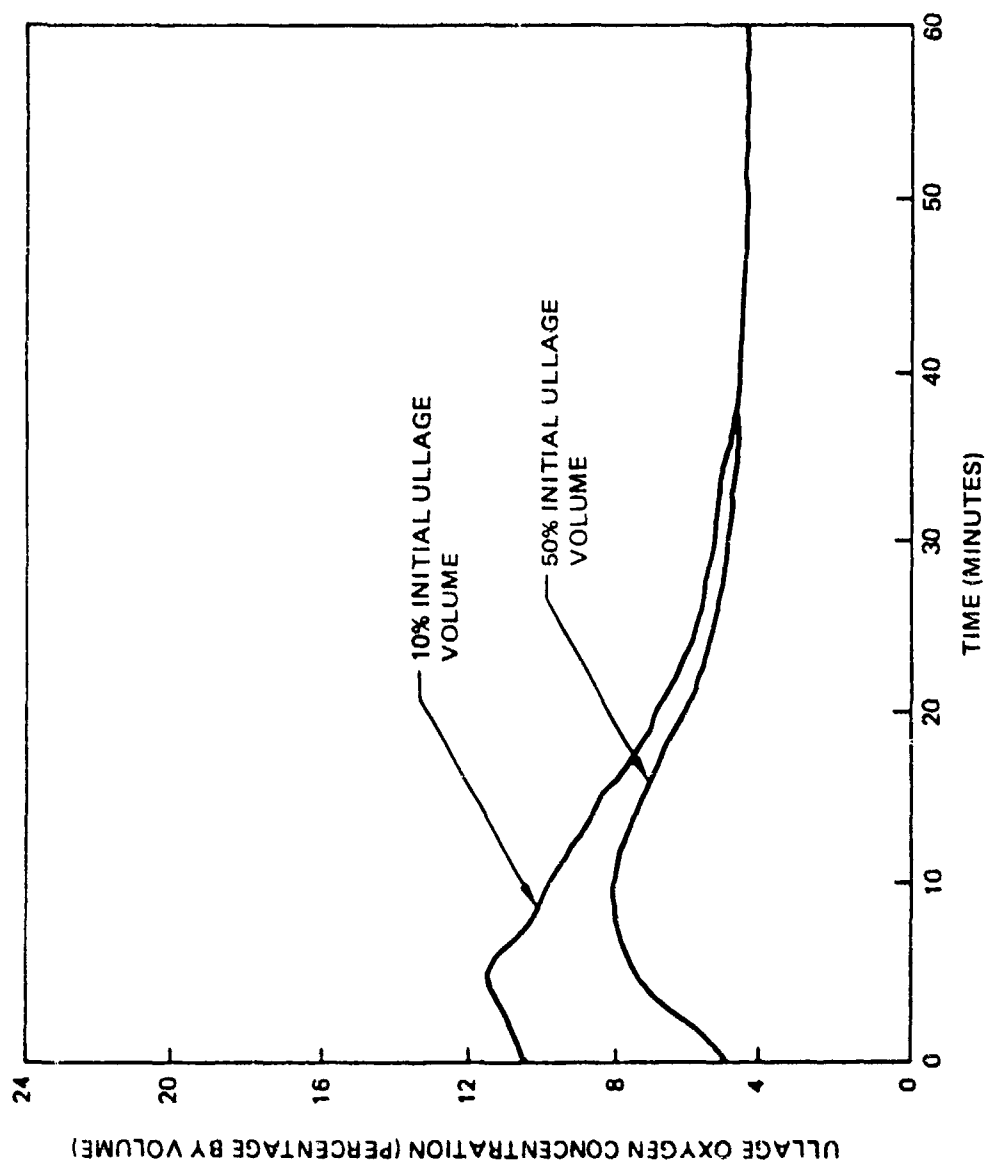
mid-ullage measurements shown in Figure 30. The peak O_2 level at 10% ullage is seen as 12% by volume concentration compared to a peak value of 8.5% for the 50% ullage.

Ullage gas stratification effects were not as pronounced with decreasing pressure (simulated climb) compared with the constant pressure tests. This effect is illustrated in Figure 31 where the estimated variation is 2.2% for climb and 3% for constant pressure with a 50% ullage volume. This reduced stratification is probably due to the increased ullage gas mixing resulting from venting of ullage gases during the simulated climb.

3.3.3.2 Effect of Scrub Flow

As expected, the scrub flow rate had a significant effect on ullage composition during a simulated climb. As indicated in Figure 32, for a 10% ullage volume, the oxygen level with no scrubbing reached the 9% limit after 22 minutes and increased to nearly 24% after 40 minutes of simulated climb. In contrast, scrubbing the fuel with 0.1 pound per minute of NEA_5 resulted in a oxygen concentration profile which is typical of efficient scrubbing. In the initial part of the simulated mission, the fuel contains relatively high amounts of dissolved oxygen which caused the ullage oxygen concentration to increase somewhat above the 9% safe limit. As the simulation continued, the fuel was depleted of dissolved oxygen until the fuel dissolved oxygen was in equilibrium with the oxygen level in the NEA_5 . This oxygen schedule is evident in Figure 32 which shows that the oxygen concentration asymptotically approaches about 5%, the oxygen concentration in NEA_5 . Note that the ullage oxygen will be influenced by the vapor pressure of the fuel. Therefore, when scrubbing with NEA_5 as in this case, the final ullage oxygen concentration would be less than 5% if the concentration of fuel vapor was significant.

The data with no fuel scrubbing are consistent with data published by Parker-Hannifin (Ref. 2) on oxygen evolution effects from fuel. The high O_2 concentration without fuel scrubbing is a reflection of the greater solubility of O_2 than N_2 in jet fuel. This solubility difference results in a disproportionately smaller decrease in the equilibrium partial pressure of oxygen than of nitrogen as the equilibrium pressure is reduced. Thus, the ratio of oxygen to nitrogen partial pressures in solution (or in equilibrium



- CONDITIONS:
- 573 GALLON SAFTE TANK
 - NEA₅ SCRUBBING FLOW AT 0.1 LB/MIN
 - SIMULATED KC-135 CLIMB
 - TANK VENTED TO AMBIENT
 - JP-4 FUEL, CONSTANT TEMPERATURE

Figure 30. Mid-Ullage Oxygen Concentration for Constant Volume Simulated Climb With Scrubbing at 10% and 50% Initial Ullage Volumes

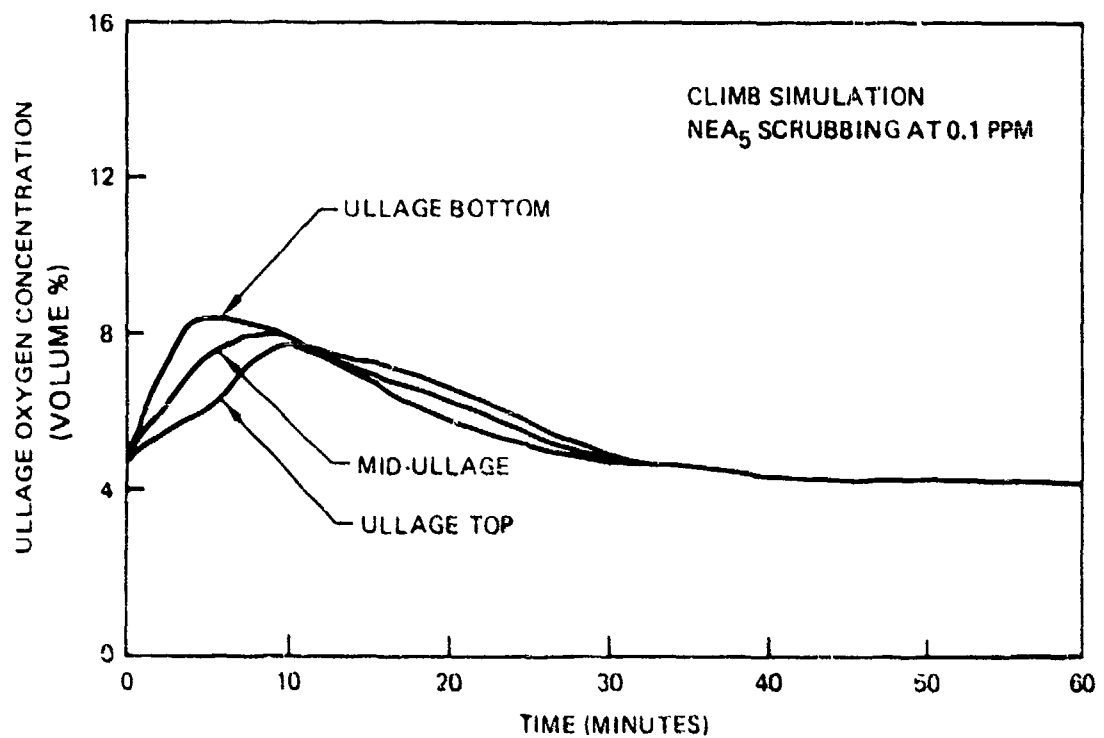
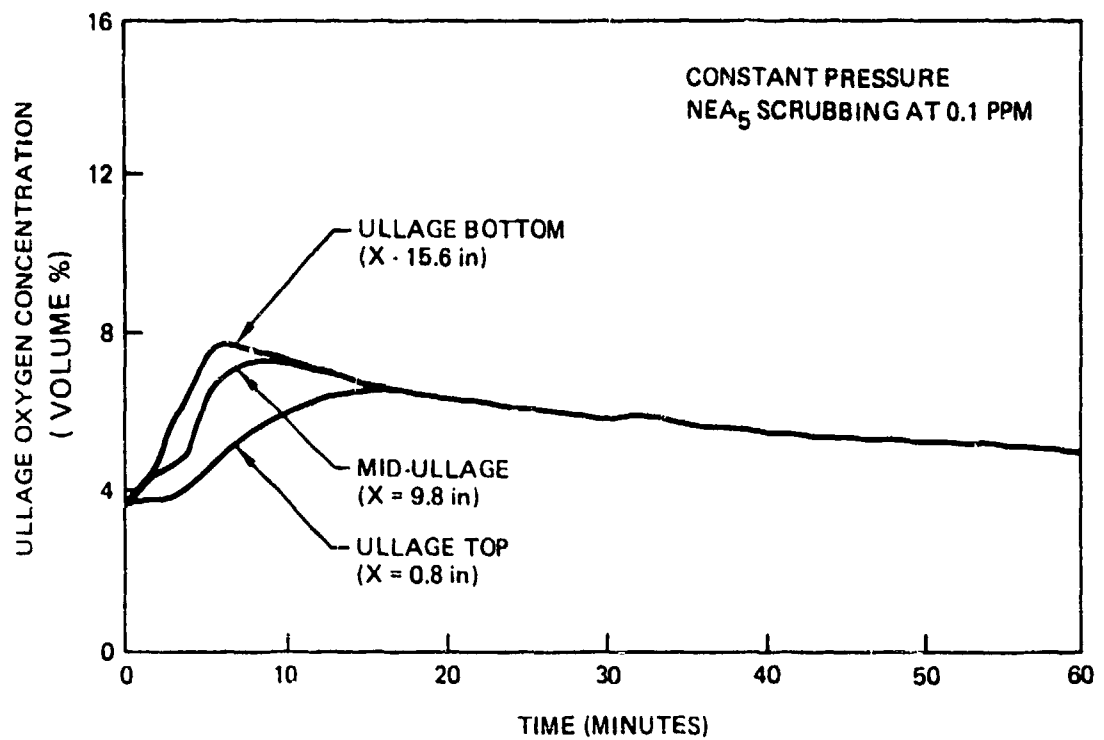


Figure 31. Spatial Variation of Oxygen Concentrations for Constant Volume Scrubbing at 50% Ullage Volume with and Without Simulated Climb

- CONDITIONS:
- 573 GALLON SAFTE TANK
 - 10% INITIAL ULLAGE VOLUME
 - SIMULATED KC-135 CLIMB WITHOUT DEPLETION
 - TANK VENTED TO AMBIENT
 - JP-4 FUEL, CONSTANT TEMPERATURE

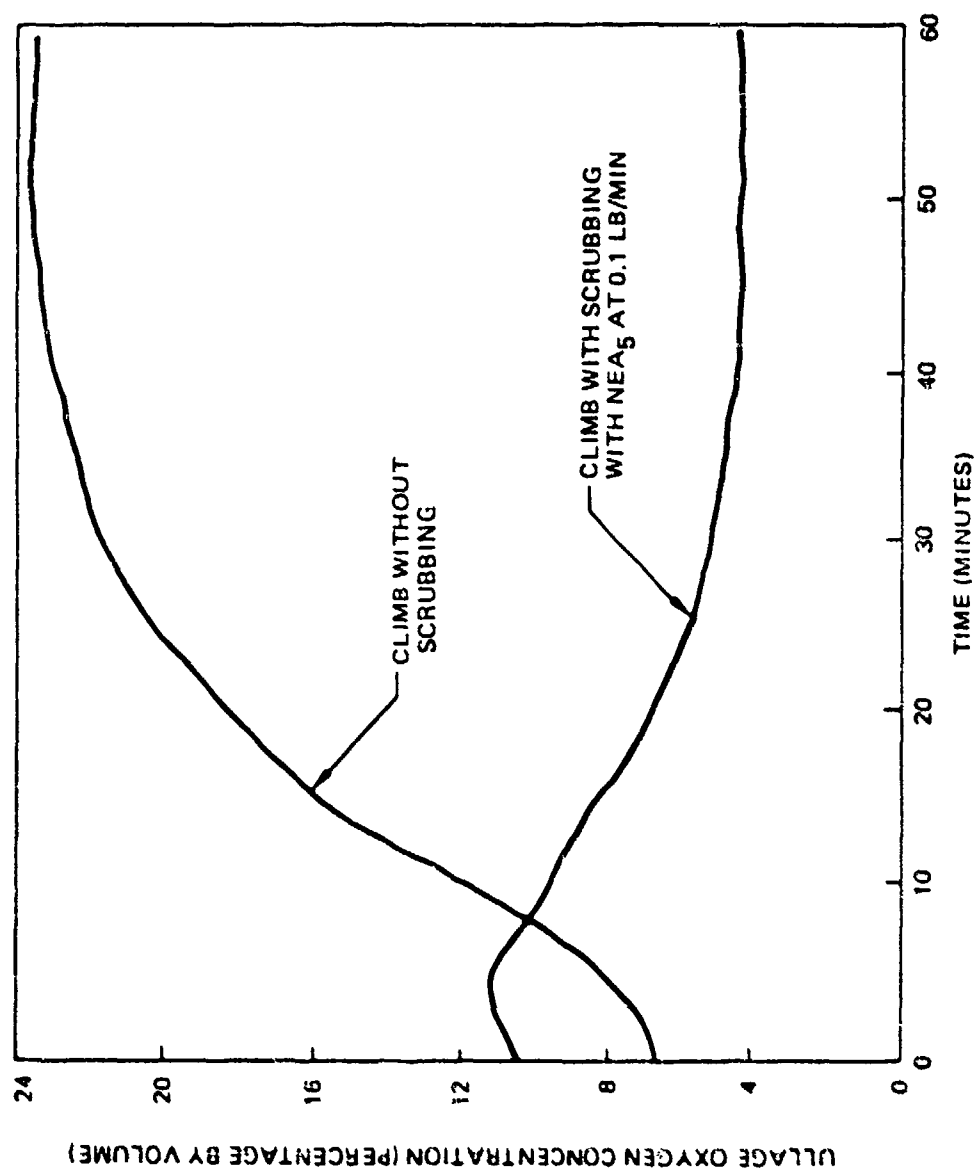


Figure 32. Mid-Ullage Oxygen Concentration for a Simulated Climb With and Without Scrubbing at 10% Initial Ullage Volume

with the liquid phase) increases from the sea level ratio as gas is removed from solution. For example, at 13.8 psia (\approx 1700 feet), the ratio of partial pressures is 27.3% compared to 26.5% at sea level.

As in the previous 10% ullage tests, the agreement between ullage probes for both the scrub and no scrub cases was to within 2%, indicating only a modest degree of stratification (see Figure 33).

3.3.3.3 Effect of Vibration and Fuel Circulation

The individual and cumulative effects of tank vibration and fuel circulation are presented in Figure 34. As indicated in the figure, vibration affected the gas evolution rate more than circulation. However, the gas evolution rates for vibration alone and combined circulation and vibration were very similar. The figure also illustrates the differences in oxygen concentration with and without circulation and vibration when the initial oxygen concentrations are the same. The maximum difference is about 10% near the mid-point of the simulated climb but decreases to about 4% at the end of the climb.

3.3.3.4 Comparison with Predicted Results

A comparison of measured and predicted ullage concentrations from this test and Ref. 2 provides some useful insights. Figure 35 shows the prediction results for both the SAFTE constant volume evolution only case (no scrubbing) and a Ref. 2 test involving a different set of tank and pressure conditions. The prediction program (Appendix A) models gas dissolution, evolution, and ullage mixing for any desired fuel type, temperature schedule, pressure schedule, fuel volume and scrubbing technique. A comparison of the Ref. 2 data and the prediction results (right hand figure) shows agreement to within 1%, which is good considering the variations possible within the ullage. A similar comparison between measured and predicted levels for the SAFTE tank constant volume simulated climb test (left hand figure) also shows good agreement but only for the case where there is tank and fuel motion (i.e. vibration and circulation). The prediction program assumes that gases are in continuous equilibrium in terms of total pressure (i.e., that after each time

- CONDITIONS:
- 573 GALLON SAFTE TANK
 - 10% INITIAL ULLAGE VOLUME (CONSTANT VOLUME)
 - 3 PROBES AT TOP, MID AND BOTTOM ULLAGE
 - TANK VENTED TO AMBIENT
 - JP-4 FUEL, CONSTANT TEMPERATURE

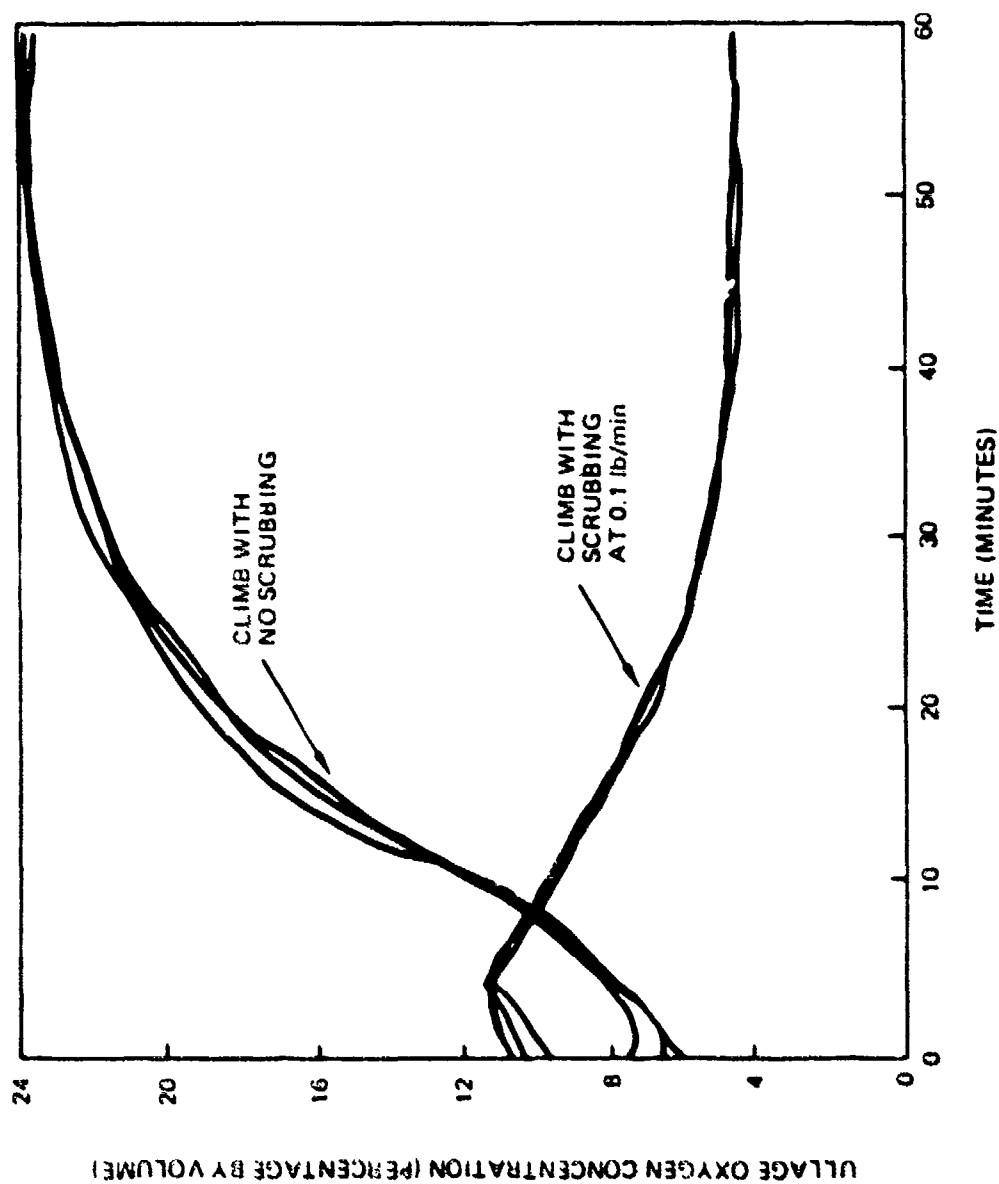


Figure 33. Spatial Variation of Oxygen Concentrations for Constant Volume Simulated Climb with and Without Scrubbing at 10%

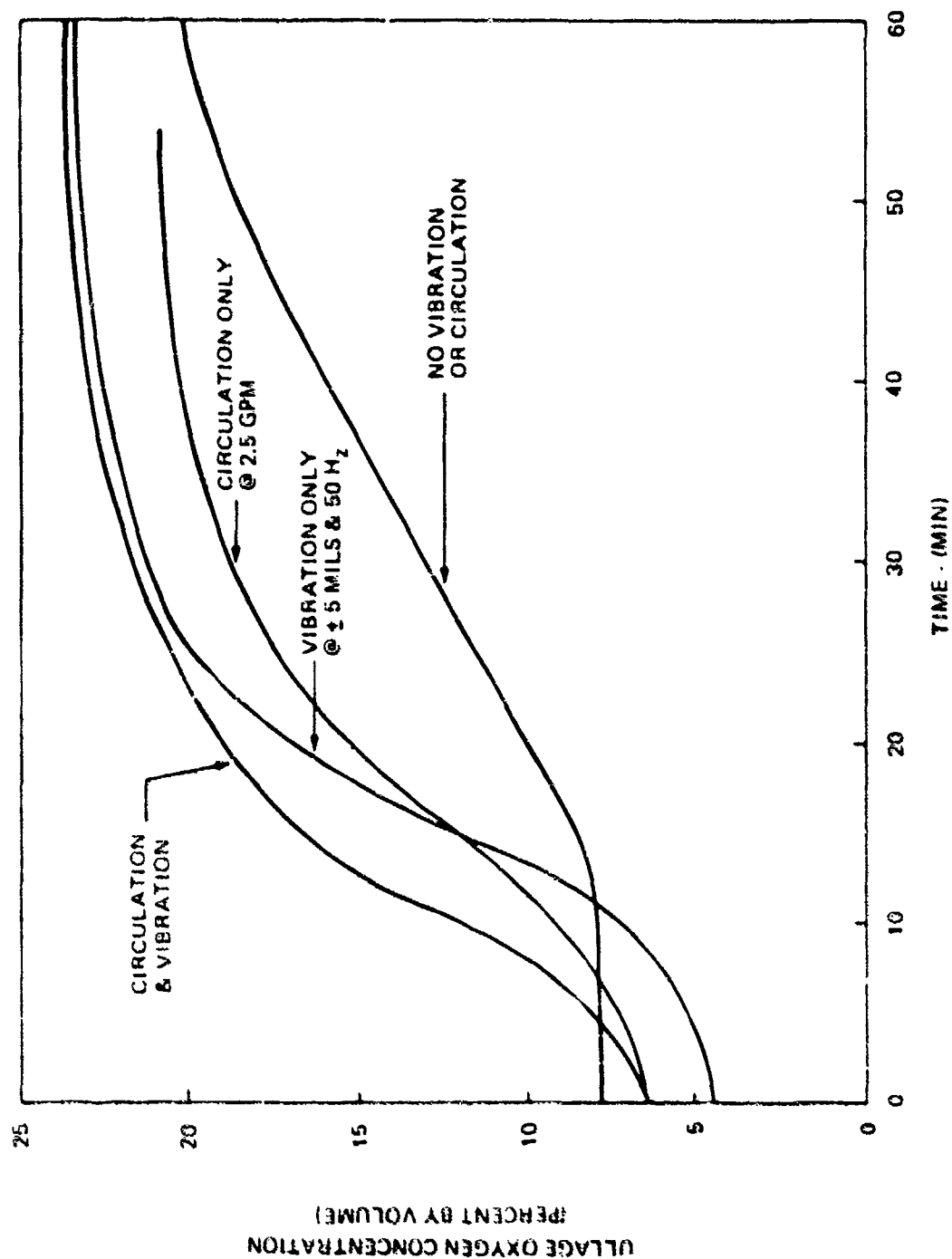


Figure 34. Effect of Fuel Circulation and Tank Vibration on Oxygen Evolution Rate During XC-135 Simulated Climb Without Scrubbing at 10% Ullage Volume

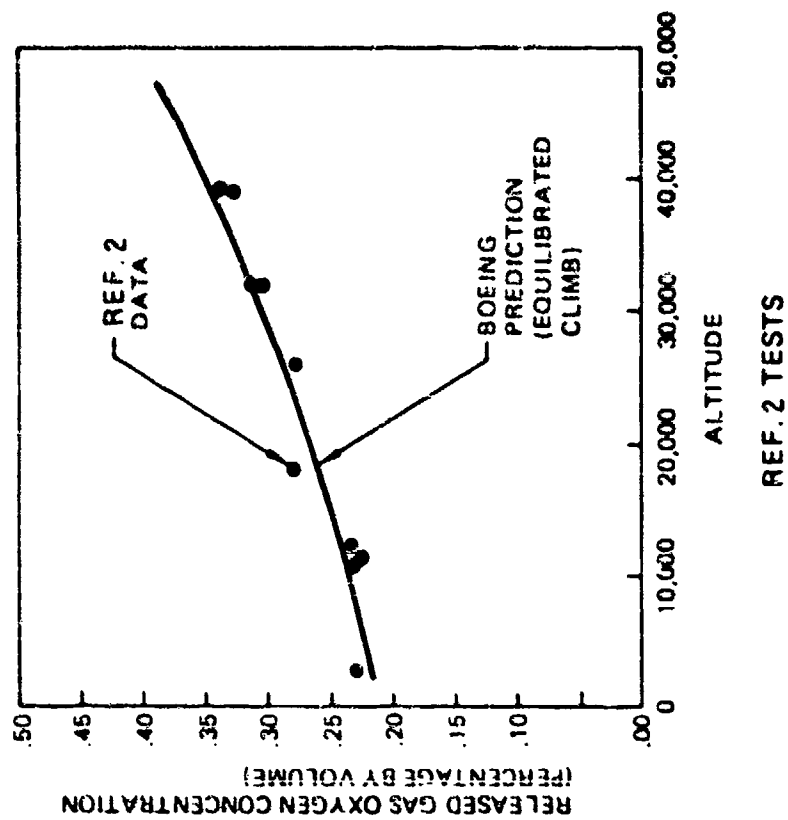
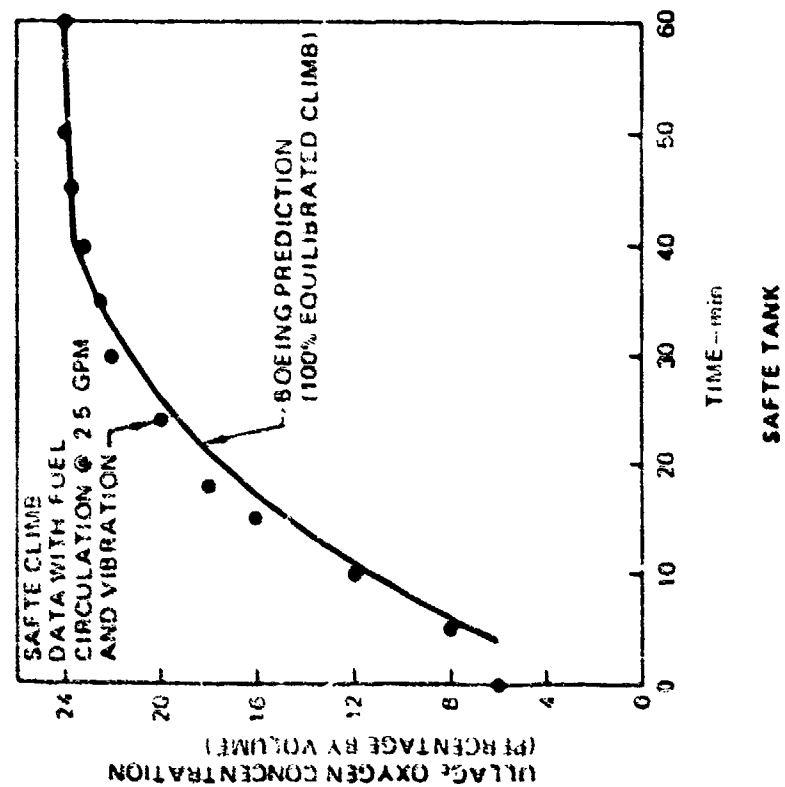


Figure 35 Measured and Predicted Ullage Oxygen Concentration for a Simulated Climb Without Scrubbing

step the maximum allowable quantity of gas evolves from the fuel to the ullage). This lack of equilibrium suggests from the SAFTE measurements that equilibrium evolution occurs only when there is vigorous tank and fuel motion; in the quiescent climb case the fuel is apparently supersaturated with dissolved air since the rate of the evolution is greatly reduced. The consequences of this effect will be discussed in a later section.

3.3.3.5 Tank Observations

Observations were made through the SAFTE tank viewing window to evaluate the extent of bubble formation in the fuel prior to and during the simulated climb test. The following observations were made:

- o During air scrubbing (to approximate initial air saturation of the fuel), the majority of the air bubbles disappeared 15 seconds after the scrub flow was turned off. Some bubbles could be seen up to 2 minutes after cutoff after which no bubbles were evident. The fuel maintained a milky appearance after 2 minutes.
- o No bubbles appeared during the ullage shutdown with NEA except during a momentary pressure drop at which time bubbles were seen.
- o No bubbles were evident for the entire simulation climb (down to a tank pressure of 5.3 psia) though the milky quality of the fuel may have increased.

3.4.4 Results of KC-135 Mission Simulations

The mission simulation tests were limited to evaluating the effect of initial ullage volume on ullage concentrations as both fuel volume and tank pressure was decreased. The comparison between the 10% and 50% ullage cases follows the trend of the earlier tests, namely that in the larger ullage the total oxygen concentration is less affected by O_2 evolving from the fuel (either with or without scrubbing gas) due to the weaker diluting effect of the larger volume. This trend is illustrated in Figure 36 which presents oxygen concentration data for the KC-135 mission simulation with fuel depletion tests for 10% and 50% initial ullage volumes. The peak oxygen concentration values are about 14.8% for the small ullage and 9.5% for the large ullage.

- CONDITIONS:
- 573 GALLON SAFTE TANK
 - KC-135 SIMULATED CLIMB & FUEL DEPLETION
 - NEA₅ SCRUB FLOW AT 0.1 LB/MIN
 - TANK VENTED TO AMBIENT
 - JP-4 FUEL, CONSTANT TEMPERATURE

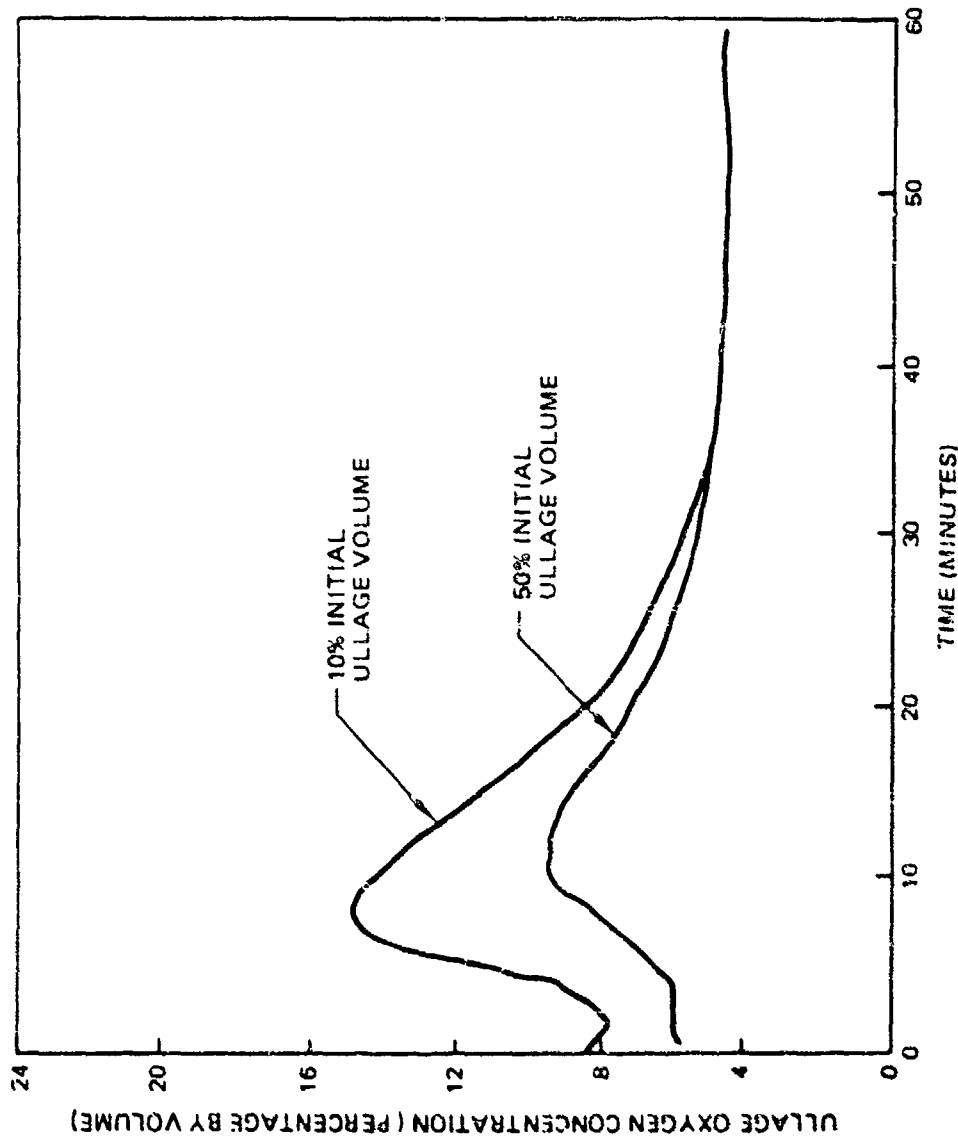


Figure 36. Mid-Ullage Oxygen Concentrations for KC-135 Simulation With Scrubbing at 10% and 50% Initial Volumes

Fuel depletion rate is seen as an important factor in the gas evolution process. A comparison of peak ullage O_2 concentration for the fuel depletion and constant volume cases shows significantly higher O_2 values with fuel depletion. These higher O_2 values are illustrated in Figure 37 which compares depletion and no depletion cases for a simulated climb with 10% ullage and scrubbing. The difference in peak values is about 4.5%.

In comparing the 50% ullage cases (climb, scrubbing and depletion versus no depletion), the difference in peaks is less dramatic being approximately 1.5% (9.5% versus 8% for the no depletion case). This smaller difference is due to the dilution effects of the larger ullage as mentioned.

3.4 DISCUSSION OF RESULTS

Results of the SAFTE tank tests suggest several factors that affect the rate of gas evolution from jet fuel. These factors are ranked in importance and discussed below.

Presence of Scrub Gas:

At the design scrub gas and motive fuel flow rates, this effect is significant in limiting ullage inert time (i.e. above 9% O_2 concentration) and in shifting the O_2 concentration peak to an earlier portion of a climb period.

Tank Pressurization:

When combined with scrub flow, the total amount of gas released is greater for a climb condition than for level flight. The resulting ullage is, therefore, more oxygen rich (and potentially hazardous) during the pressure decrease associated with the climb.

- CONDITIONS:
- 573 GALLON SAFTE TANK
 - 10% INITIAL ULLAGE VOLUME
 - NEA₅ SCRUB FLOW AT 0.1 LB/MIN
 - TANK VENTED TO AMBIENT
 - JP-4 FUEL, CONSTANT TEMPERATURE

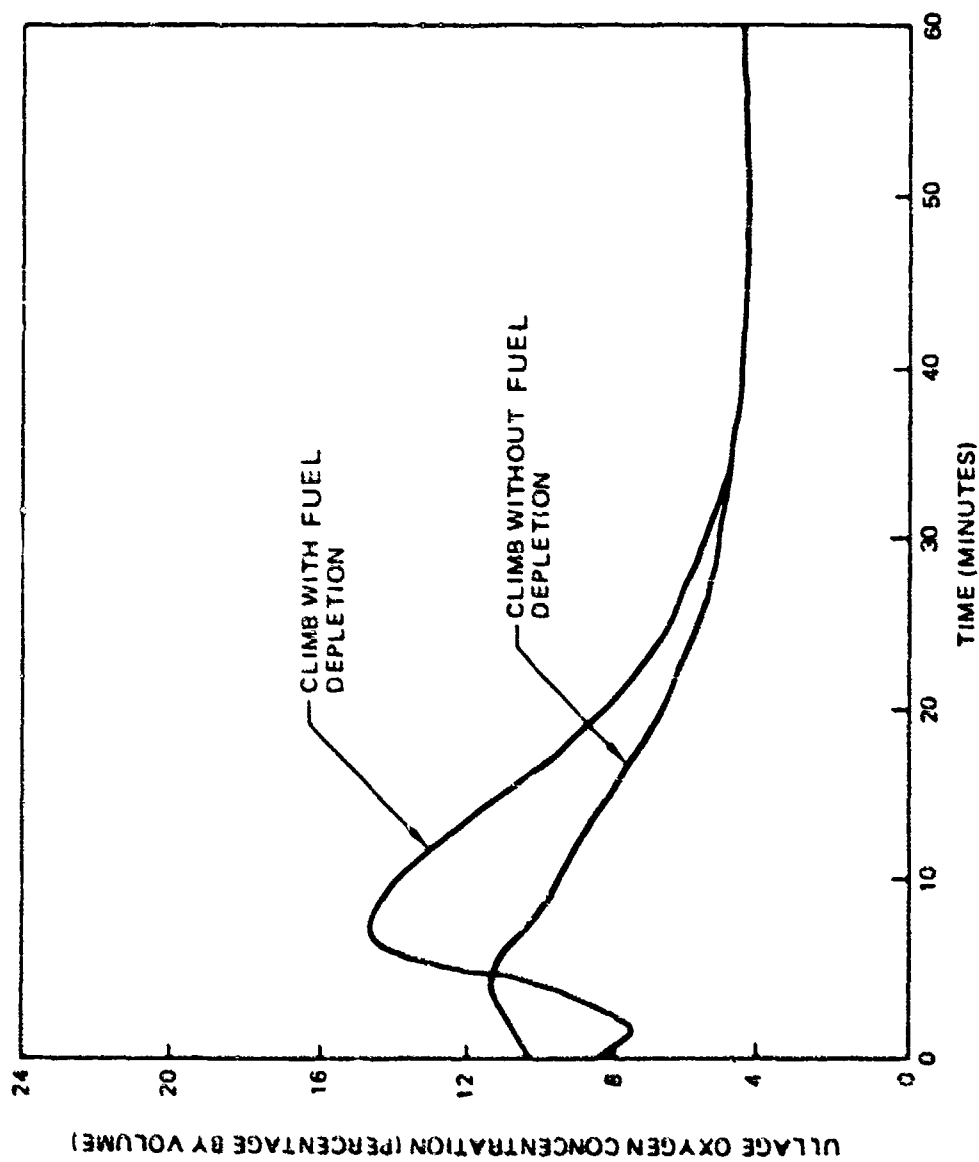


Figure 37. Mid-Ullage Oxygen Concentrations for 10% Initial Volume with Scrubbing With and Without Fuel Depletion

Ullage Volume:

Larger ullages are less sensitive to gas evolution effects because of dilution effects and the quantity of fuel dissolved gas available (when a larger ullage corresponds to a smaller fuel volume). Stratification seems to be more pronounced for larger ullages than for smaller ones suggesting the added risk of localized combustion zones. Thus, in larger volumes the benefits of a scrub gas may be delayed until the entire ullage is sufficiently mixed with the nitrogen-rich evolving gas.

Fuel Circulation:

Fuel circulation is important when the scrubbing system is inactive (the effect is masked when scrubbing is active). A quiescent climb has the potential for explosive gas release if the tank is suddenly vibrated, resulting in foaming, loss of fuel, and possible structural damage. Fuel scrubbing provides adequate fuel motion to make this situation unlikely.

Fuel Depletion

During fuel depletion, part of the gas needed to maintain pressure comes from the vent or repressurization system and part from gas evolving from the fuel. In many fuel systems, tank pressure is controlled to a band width of one to two psi by means of a discharging relief valve (or climb valve) at maximum pressure. Potentially, then, gas can evolve as the tank pressure drops from maximum to minimum allowable pressure during fuel depletion. This gas evolution may result in local combustible zones even if the ullage is nominally inert.

Among the most important trends observed in this test is that a larger ullage is more likely to be stratified as a result of gas evolution than a smaller ullage. This observation is reasonable since during evolution, gas is added to the ullage only from the fuel surface and at low velocity. Low gas flow rates near the fuel interface may form a vulnerable, combustible mixture near

the fuel surface. These vulnerable zones may be set up under several airplane mission conditions, including:

- o when the climb scrub system is first turned on;
- o during multiple climb and descent legs; and
- o during extended cruise legs where fuel depletion (and pressure reduction) causes oxygen to evolve from the fuel.

Another important trend is that climb scrubbing or even fuel circulation tends to reduce stratification and therefore improves the certainty of any ullage vulnerability assessment. Thus, two extremes of ullage gas uniformity can be identified from this test: (1) the near well-stirred case represented by a small ullage during a period of fuel scrubbing or other vigorous fuel motion and, (2) the highly stratified case characteristic of a large ullage volume in the absence of significant fuel motion or scrubbing gas inflow.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Tests conducted in the Boeing Fuels Laboratory in Seattle and the SAFTE facility at WPAFB were very beneficial both in validating the prediction process and directing attention to areas of the analytical modeling process which require further study. Tests involving vigorous mixing of air saturated fuel and inert ullage gases revealed that the final ullage oxygen concentration could be predicted quite well for JET A fuel. The differences between predicted and measured values were larger for JP-4 fuel, suggesting the importance of including the fuel vapor pressure in the modeling process. The fuel scrubbing tests at Seattle revealed that the agreement between measured and predicted oxygen concentrations was quite good for tests in which air saturated JET A fuel was scrubbed with GN_2 and NEA. As expected, longer scrubbing times were required for NEA than for GN_2 to achieve a given ullage oxygen concentration. Performance mapping of the C-5A scrub nozzle revealed that the appropriate conditions for testing the nozzle in the SAFTE facility were a flow rate of 2.36 gallons per minute at a pressure of 57 psig with an inert gas flow rate of 0.0925 pounds per minute.

Fuel scrubbing tests at constant volume and pressure in the SAFTE facility showed that the peak oxygen concentration was higher but stratification of ullage gases was greatly reduced for a 10% ullage volume compared to a 50% ullage volume.

Tests with a simulated climb in the SAFTE facility but at constant volume revealed similar trends to the constant pressure and volume tests. Ullage O_2 concentrations had higher peaks with a 10% ullage than with a 50% ullage. However, ullage gas stratification was not as pronounced with the simulated climb tests compared with the constant pressure tests. The effect of scrub flow was about as predicted. Without scrubbing, the ullage O_2 concentration quickly exceeded the 9% limit with an initially inert ullage and increased to a peak value of about 24% at the end of the simulated climb. Conversely, scrubbing maintained an inert ullage for the majority of the climb. The exception was during the first 12 minutes in which the majority of oxygen removal occurred. In the fuel tank vibration and circulation tests, vibration had a larger effect on stimulating dissolved oxygen to evolve from the fuel than did circulation; combining vibration and circulation had no

greater influence on O_2 concentration than vibration by itself. Gratifying results were obtained when the ullage oxygen prediction computer code was compared with test data obtained from this and other programs.

Simulated KC-135 mission simulation tests in the SAFTE facility followed the trend of previous tests, i.e., the peak O_2 concentration was higher with a 10% ullage than a 50% ullage. The data revealed that the peak oxygen concentration was higher with a constant fuel volume. However, these results were for a vent system without climb and dive valves. If the scrub gas was not sufficient to maintain pressure during fuel depletion, evolved oxygen could be trapped in the tank until pressure adjustment occurred. Further studies are required to determine the effect of fuel depletion on peak O_2 concentrations for simulated missions utilizing realistic vent system hardware.

The most significant conclusion resulting from these tests is that an analytical model based on instantaneous equilibration during a time step, the ideal gas law, published solubility coefficients, and partial pressure relationships is sufficiently accurate to define inert gas requirements for aircraft fuel scrubbing. In addition to establishing inert gas requirements, the model provides a basis for key trade studies. For example, one may wish to examine the benefits and risks of allowing the oxygen concentration to exceed the safe limit for rarely encountered or relatively low risk flight conditions within the flight envelope. The ability to accurately define the inert gas requirements for fuel scrubbing is a vital part of the overall OBIGGS sizing procedure.

Several areas of additional research were suggested by the results of this test program, both to verify suggested trends and to explore other effects that may contribute to the observed gas evolution processes. These include:

- o Testing with more ullage probes to verify the one-dimensional effects observed. A larger probe array would reveal any important variability in the lateral direction.
- o Evaluating ullage stratification for additional ullage volume cases (25%, 75%, 90%).
- o Assessing O_2 evolution rates for a range of fuel depletion rates.
- o Simulating climb valve and demand regulator effects in conjunction with cruise and descent conditions.
- o Simulating a wider range of climatic and airplane performance conditions. This range of conditions will affect tank wall temperatures and ultimately the gas evolution process. In the current test, temperatures were held constant to achieve experimental control.
- o Assessing tank geometry effects including scrub nozzle placement and orientation, vent location and orientation, and simulated tank altitude as possible variables. It is likely that the orientation of the tank vent affects the ullage gas distribution for both ascent and descent conditions.

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APPENDIX A

ANALYTICAL MODEL FOR FUEL SCRUBBING

Consider a mass of fuel, M_f , at temperature T , and given mass of scrub gas, M_i , as shown in Figure A1. The scrub gas, a binary mixture of oxygen and nitrogen, is injected into the fuel, thoroughly mixed (e.g., by shaking) with existing dissolved gases until equilibrium is attained. It is assumed that during the process the total pressure remains constant and evolved gases are at the equilibrium composition. For constant total pressure scrubbing:

$$P_{O_1} + P_{N_1} = P_{O_2} + P_{N_2} = P_t - P_v \quad (A1)$$

where,

P_{O_1}, P_{N_1} = initial partial pressure of oxygen and nitrogen

P_{O_2}, P_{N_2} = final partial pressure of oxygen and nitrogen

P_t = total system pressure

P_v = fuel vapor pressure at fuel temperature, T

Mass balances for each component are:

scrub gas + dissolved gas = released gas + dissolved gas
(before equilibration) (after equilibration)

$$m_{O_1} + (\beta_O \cdot V_F \cdot P_{O_1}) / (R_O \cdot T) = m_{O_2} + (\beta_O \cdot V_F \cdot P_{O_2}) / (R_O \cdot T) \quad (A2)$$

$$m_{N_1} + (\beta_N \cdot V_F \cdot P_{N_1}) / (R_N \cdot T) = m_{N_2} + (\beta_N \cdot V_F \cdot P_{N_2}) / (R_N \cdot T) \quad (A3)$$

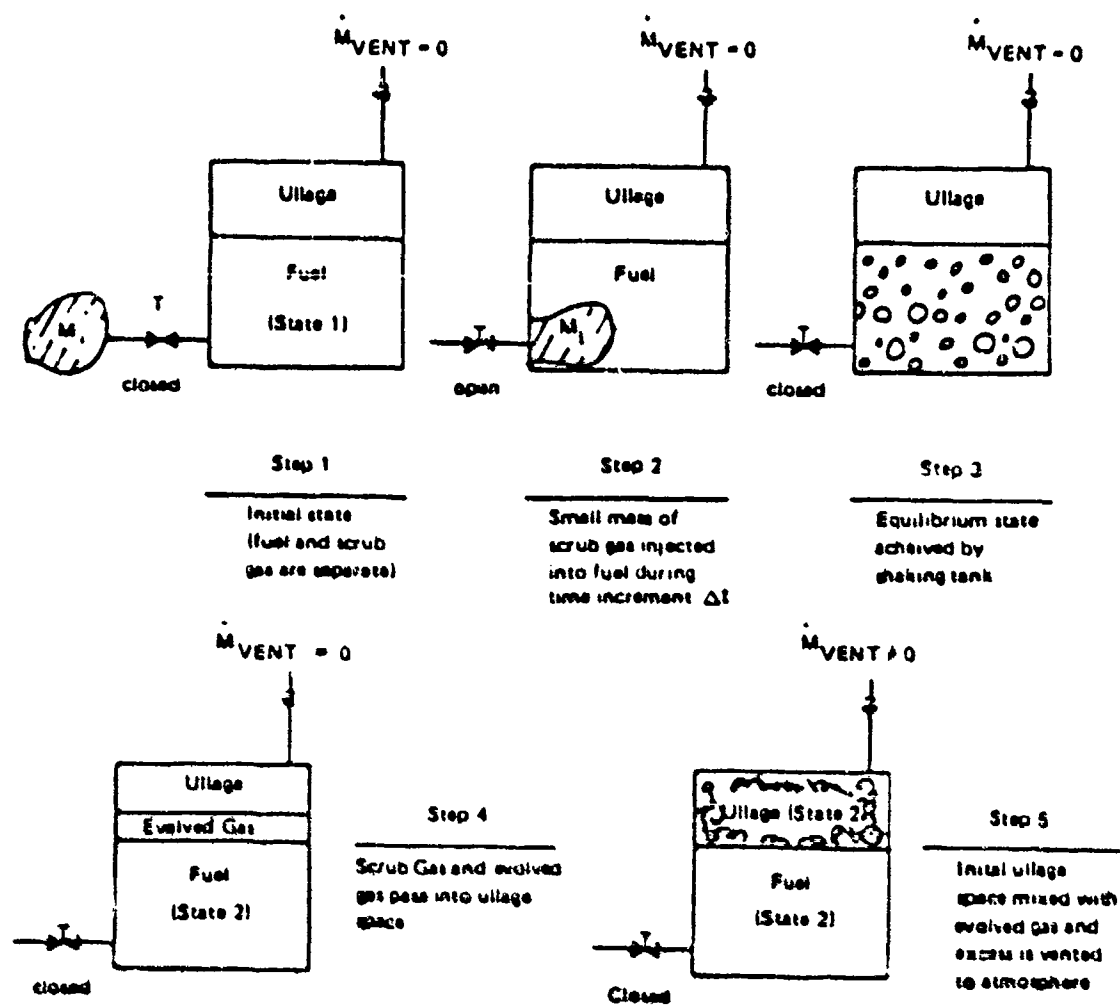


Figure A1 Pictorial Representation of Boeing Fuel Tank Analytical Model

where,

m_{O_1} , m_{N_1} = masses of oxygen and nitrogen introduced by the scrub gas

m_{O_2} , m_{N_2} = final masses of oxygen and nitrogen released from the fuel

V_F = fuel volume

R_O = gas constant for oxygen

R_N = gas constant for
nitrogen

T = fuel temperature

β_O = Ostwald solubility

coefficient for oxygen

β_N = Ostwald solubility

coefficient for nitrogen

The equations of state for the released oxygen and nitrogen are:

$$P_{O_2} = \frac{m_{O_2}}{V} \left(\frac{R}{M_O} \right) T \quad (A4)$$

$$P_{N_2} = \frac{m_{N_2}}{V} \left(\frac{R}{M_N} \right) T \quad (A5)$$

where,

M_O , M_N = molecular weights of oxygen and nitrogen, respectively

V = gas volume

R = universal gas constant

Equations A1 through A5 contain 5 unknowns, namely,

P_{O_2} , P_{N_2} , M_{O_2} , M_{N_2} and V .

The equations can be reduced to the form:

$$P_{O_2}^2 A + P_{O_2} B + C = 0 \quad (A6)$$

where,

$$A = V_F (\beta_O - \beta_N) / (R_N \cdot T)$$

$$B = [V_F / R_N \cdot T] [\beta_N (P_t - P_v - P_{N1}) - \beta_O (P_t - P_v + P_{O1})] - m_{N_1} \cdot + (Q \cdot m_{O_1})$$

$$C = [V_F \cdot \beta_O \cdot (P_t - P_v) P_{O1} / (R_N \cdot T)] + [Q \cdot m_{O_1} \cdot (P_t - P_v)]$$

and

$$Q = i_N/M_0$$

The solution of P_{O_2} , the equilibrium partial pressure of oxygen after scrubbing, from equation (A6) is now straightforward. The new equilibrium partial pressure can be used to determine the quantity of released gases and, therefore, the time varying ullage concentrations.

APPENDIX B

CALCULATION METHOD TO DETERMINE THE REQUIRED SCRUB FLOW RATES FOR THE USAF SAFTE TANK

Data derived from Lockheed and Parker-Hannifin literature on the C-5A fuel scrubbing system produced the following results:

- o On-Board Fuel Volume = 40,944 GAL
- o Total Inert Gas (GN_2)
Scrub Flow Rate = 7.892 PPM
- o Total Fuel Motive Flow Rate = 191.20 GPM

From these data, the following ratios were derived, representing the average operating points of the C-5A scrub system:

$$\frac{\text{Tank Volume}}{\text{Motive Fuel Flow}} = \frac{256 \text{ Gallons Fuel}}{\text{GPM Motive Flow}} \quad (\text{B1})$$

and,

$$\frac{\text{GN}_2 \text{ Gas Flow}}{\text{Motive Fuel Flow}} = \frac{0.0413 \text{ PPM GN}_2 \text{ Flow}}{\text{GPM Motive Flow}} \quad (\text{B2})$$

The first ratio relates to the fuel flow rate per tank volume used in the C-5A to distribute the scrub gas in the fuel tank.

The second ratio is the more fundamental in that it defines the mixing ratio of the gas and fuel streams (on average) for the nozzles used in the C-5A.

The specific nozzle used in these tests (and planned for the SAFTE tank) was designed for a small fuel bay of the No. 1 auxiliary tank of the C-5A with an estimated fuel volume of 303 gallons. Thus, the design fuel motive flow of the nozzle is:

$$\text{C-5A Design Motive Fuel Flow} = 303 \text{ gallons} \div \frac{256 \text{ gallons}}{\text{GPM Motive Flow}}$$

$$= 1.2 \text{ GPM Motive Flow}$$

with a corresponding gas flow of:

$$\text{C-5A GN}_2 \text{ Scrub Gas Flow} = 0.0413 \text{ PPM Gas Flow} \times \frac{1.2 \text{ GPM}}{\text{GPM Motive Flow}}$$

$$= 0.05 \text{ PPM GN}_2 \text{ Flow}$$

A design scrub flow rate of 3 PPM NEA₅ was established for the KC-135 airplane based on previous Air Force and Boeing data. Based on a KC-135 airplane fuel capacity of 17,625 gallons, the following operating points for the 573 gallon SAFTE tank are appropriate:

$$\begin{aligned} \text{o SAFTE NEA}_5 \text{ Scrub Flow Rate} &= 3 \text{ PPM} \times \frac{573}{17,625} \\ &= 0.0975 \text{ PPM NEA}_5 \end{aligned}$$

From Equation B2,

$$\text{o SAFTE Fuel Motive Flow} = 0.0975 \text{ PPM NEA}_5 \div \frac{0.0413 \text{ PPM Gas Flow}}{\text{GPM Motive Flow}}$$

$$= 2.36 \text{ GPM Fuel Motive Flow}$$

These operating points are indicated in Figure 5.

The high motive flow rate for the SAFTE tank relative to the C-5A operating point (2.36 GPM versus 1.2 GPM) is a reflection of the larger SAFTE tank volume (573 gallons versus 303 gallons for the C-5A test tank).

APPENDIX C

CALCULATION OF NOZZLE SCRUB EFFICIENCY FROM BOEING SCRUB EVALUATION TESTS

The scrubbing efficiency, η , may be defined as the ratio of actual O_2 mass removed to the ideal O_2 mass removed from the fuel, i.e.

$$\eta = \frac{\text{actual mass removed}}{\text{ideal mass removed}} = \frac{(1 - \frac{O_2 \text{ remaining}}{O_2 \text{ total}})_a}{(1 - \frac{O_2 \text{ remaining}}{O_2 \text{ total}})_i} \quad (C1)$$

where subscripts a and i refer to actual and ideal, respectively. The ideal mass removed by scrubbing is considered a perfect mixing process between the fuel and scrub gas. Therefore, the predicted fuel O_2 concentration can be expected to be less than the measured values. On the other hand, the predicted O_2 concentration in the ullage will tend to be higher than measured. High efficiencies are associated with large numbers of small bubbles uniformly distributed throughout the liquid while lower efficiencies would occur with a lower number of larger bubbles.

Data from the scrub nozzle evaluation (Section 3.0) with 0.037 pounds per minute scrub flow is presented in Table C1. Substituting the table values into equation (C1) above gives:

$$\text{Scrubbing Efficiency} = \eta = \frac{1.0 - 0.3080}{1.0 - 0.2161} = \frac{0.692}{0.784} = 0.883 \text{ or } 88\%$$

Table C1

Summary of Values Used in Scrub Nozzle Efficiency Calculation

Quantity	Ideal (Computer)	Actual
	Code	(test data)
1. Total volume (ft ³)	20.8	20.8
2. Ullage volume (ft ³)	2.08	2.08
3. Dissolved O ₂ in fuel (vol fraction)	0.07	0.10
4. Dissolved O ₂ in fuel (mass fraction)	0.079	0.113
5. Total O ₂ (lbm)	0.087	0.087
6. Total N ₂ (lbm)	0.1507	0.1507
7. Total dissolved gas (lbm)	0.2376	0.2376
8. Remaining O ₂ (line 4 x line 7)	0.0188	0.0268
9. O ₂ remaining/total	0.2161	0.3080